SEDIMENTOLOGY, COAL CHEMISTRY AND PETROGRAPHY OF THE CRETACEOUS MORLEY COAL MEASURES AND THE EOCENE BEAUMONT COAL MEASURES, OHAI COALFIELD, SOUTH ISLAND, NEW ZEALAND

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AA
FOOTBALL GROUND
SQUASH COURTS
AA
OHAI
8 km
AA
COAL MINE

Undoubtably most geologists at some stage in their career have considered the advantages of a time machine which would deliver them to a critical site on the paleolandscape. Unfortunately, such means of performing research are not available and we must resort to our imagination and the scientific method.

S.A. Schumm

Nothing in life is worthy of great anxiety.

Plato

ABSTRACT

Several kinds of data from the Cretaceous Morley and Eocene Beaumont Coal Measures at Ohai Coalfield were integrated in order to develop models for sedimentary clastic deposition and mire formation. These data comprise lithostratigraphic relationships at outcrop and basin scale and information on coal chemistry, petrography and palynology. Results indicate that although deposition of both Morley and Beaumont Coal Measures were tectonically controlled by the development of sedimentary sub-basins, Cretaceous mires and sedimentary regimes differ from those of the Eocene.

Although the data available at Ohai Coalfield are insufficient for interpretation of fluvial channel planform, other characteristics of the sedimentary environments can be deduced. Accumulation of the Morley Coal Measures occurred in two types of non-contemporaneous environment, 'S'-environments, in which widespread sand was deposited by fluvial channels and few mires developed, and 'C'-environments in which only fine-grained clastic deposition occurred and mires were extensive and persistent. Three environments, which were sometimes contemporaneous, have been identified in the Beaumont Coal Measures. In Beaumont 'S'-environments, sandy clastic sediment was deposited widely by fluvial channels whereas in the 'C'- and 'C-S'-environments, mires developed and sedimentation in shallow lakes and streams was widespread. In the 'C'-environments channels carried mud with little sand but in the 'C-S'-environments sand deposition was more common.

Morley mires, which were larger and longer-lived than Beaumont mires, were rarely flooded and may have been domed. In contrast, Beaumont mires were frequently flooded and probably not domed. Most Morley mires developed in environments with widespread mires drained by low energy streams. In contrast high energy fluvial activity was more common in Beaumont mire-forming environments; Beaumont mires are inferred to have frequently developed on lake margins. Palynological evidence indicates that the Morley floral assemblage was dominated by gymnosperms whereas both angiosperms and gymnosperms formed significant proportions of the Beaumont flora.

The information available on Morley coal allows development of a model for peat accumulation. Peat accumulation was influenced by a number of interdependent parameters including water table level, nutrient supply and acidity. In response to environmental conditions two different peat types formed. At the base, top and margins of mires peat was generally woodier, less degraded and less oxidised. In contrast, peat in the mire centres suffered both more non-oxidative degradation as well as oxidation and contained less woody material. As mires developed, the initially diverse gymnosperm flora became dominated by the podocarp *Phyllocladidites mawsonii* ; however this change in vegetation did not affect the character of the peat.

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CHAPTER 1

INTRODUCTION

1.1 GENERAL SETTING

Ohai Coalfield is located in the southern part of the South Island, New Zealand (Fig. 1.1), 77 km northwest of Invercargill (Fig. 1.1 inset). The coalfield extends over an area of 100 square kilometres. Ohai Coalfield is physiographically defined by the Takitimu Mountains in the north and the Twinlaw Range in the south. To the west the coalfield opens out into the floodplain of the Waiau River into which most of the drainage from Ohai Coalfield flows. In the east the coalfield abuts Quaternary fluvial sediments of the Southland Plains.

The climate in the region of Ohai is cool-temperate. The prevailing westerly air stream is moderated by the mountain ranges to the west of Ohai. Annual precipitation at Nightcaps, one of the two townships in the area, averages 904 to 994 mm (Bowman et al., 1987). The mean daily temperatures in the coalfield range from 14.7° in January-February to 4.7°C in July and there is an average of 103 frosts per year (pers. comm. NZ Meteorological Service).

The topography of Ohai Coalfield is gently undulating. Elevation varies from 100 m to 200 m above sea level in the valley to 550 m above sea level on top of the Twinlaw Range. Most valley floors and gently sloping hillsides at Ohai Coalfield have been developed for agriculture. The steeper, less fertile areas of the hills are planted in non-indigenous forest for production of timber. The soil throughout the coalfield is generally poor and therefore unfarmed land is predominantly covered with tussock, manuka and matagouri scrub while small stands of willow and poplars line the river banks.

Coal mining and farming provide the main sources of revenue for the two towns (Ohai and Nightcaps) within Ohai Coalfield (Fig. 1.1). Ohai (population 700) and Nightcaps (population 400) are linked to Invercargill by road and rail. Other towns in the vicinity of Ohai Coalfield are Winton to the east and Otautau to the south.

1.2 PREVIOUS GEOLOGICAL WORK

Knowledge of the geology at Ohai Coalfield has developed since coal was discovered in the Ohai region in the 1850s. Captain Howell was probably the first to discover coal at Ohai (Lillie, 1945) but the first known report of coal was when J. Hector, a geologist working for the N.Z. Geological Survey, mentioned Morley Creek Coal in a Colonial

Museum Report (Lillie, 1945). Hector made a further, more detailed report in 1869 (Hector, 1869). From description of the lithologies associated with the coal, Hector correlated the Ohai strata with lithologies in Nelson, Waikato and Auckland, although he noted that Ohai coal might be less valuable than coal in the other areas. Hector considered strata from all these coal-bearing areas to be Upper Tertiary. Lillie also ascribed all Ohai coal to the Upper Tertiary in his map published in 1871 (Lillie, 1945). He noted the presence of *Unio* (now *Velesunio huttonii*), a freshwater Tertiary mollusc, in brown mudstone and also commented on the macroscopic resin in some coal seams. Hutton (1872), like Hector, thought the "Brown Coal Formation" of Ohai was very similar in quality, appearance and stratigraphical relations to the coal-bearing strata of the Waikato and Drury Coalfields. Hutton noted two coal seams at Mt Linton and Morley Creek and also coal southwest of Night Cap Hill.

Ongley (1917) and Morgan (1920) attempted to describe the structure of Ohai Coalfield in their short reports on the "Nightcaps - Mt Linton Coalfield". Both Ongley and Morgan noted the discontinuity of coal seams and the need for further work and drilling to outline the coal bearing areas. Ongley's map shows that, in the light of present stratigraphic knowledge, both Cretaceous and Tertiary age coals were being mined, although in his text Ongley states that all coal mined was Tertiary. Morgan stressed the lenticularity of seams but he considered that a large amount of coal must be present. The structure of Ohai Coalfield was also discussed by Park (1921) who, in contrast to Morgan, proposed that three coal seams, the "resin seam", the "big seam" and the "thinner coal seam", were all present over much of the Wairio and Ohai Coalfields and Quested's coal area (south of the Ohai Coalfield). The misleading simplicity of Park's description was a result of his attempt to correlate lithologies over a wide area based on little data. Further mention of structure at Ohai was made by Langford (1926) who noted the uncertainty of seam correlation and the considerable disturbance created by faulting in the coalfield. Coalfield structure is also described by Lillie (1945) and Bowen (1964). The work of Lillie and Bowen is incorporated in the following description of coalfield structure (section 1.4.3.1). The most recent structural work is that of Bowman et al. (1987) who reported on the results of extensive Coal Resources Survey drilling and seismic exploration in the eastern part of Ohai Coalfield.

The first detailed report outlining the stratigraphic nomenclature of Ohai Coalfield was that of Lillie (1945). In his stratigraphic interpretation Lillie did not recognise the presence of strata older than Tertiary. Lillie stressed the hypothetical nature of his report, in which he proposed a division of coalfield sediments into four coal horizons, each containing one or more seams. Lillie concluded that correlation in the coal measures was very difficult owing to lack of outcrop, lack of marker horizons, appearance of the same lithology at different stratigraphic intervals and the lateral variation in coal seam thickness and character; he therefore recommended that an extensive drilling programme be carried out. During the drilling programme from 1949 to 1952, Bowen examined and reinterpreted the Ohai district geology (Bowen, 1964). Bowen combined his new stratigraphic interpretation with paleobotanical work by Couper and postulated a stratigraphic nomenclature for the Ohai coal measures which was published in Suggate and Couper (1952) and Couper (1953) and later in Bowen (1964). Bowen proposed a division of the Ohai coal measures into three groups, the Lower and Middle Ohai Groups, of Upper Cretaceous age, and the Upper Ohai Group, of Upper Eocene age. Bowen's stratigraphy contained the first clear suggestion that Ohai Coalfield sediments were thought to be of Cretaceous, as well as Tertiary age. In 1964 Bowen published a bulletin on Ohai Coalfield, proposing a revised stratigraphy that is still used with only minor changes (Bowen, 1964). Bowen divided the Upper Cretaceous Ohai Group into three formations and the Eocene Nightcaps Group into two formations. He recognised six coal seams in the Morley Coal Measures and fitted these seams into the detailed paleobotanical zonation devised by Couper (1964). The problems in Couper's zonation scheme are discussed by Warnes (1988, 1990). Warnes concluded that Couper's method of palynological zonation is not reliable and devised his own method of zonation which has not yet been applied by any other authors. The most recent work on stratigraphy is that of Cave (1992) who made minor modifications to Bowen's stratigraphy. Cave also nominated some type sections as Bowen's type sections were often poorly located, incomplete and ill-defined. The stratigraphy currently used, with the nomenclature described by Turnbull et al. (1989) is shown in Figure 1.2. Cave (1992) suggests that the lithologic qualifiers used in formation names are inaccurate and therefore should be removed. However, as Cave's publication has not yet appeared, the nomenclature used by most previous authors is followed here.

Although coalfield-wide depositional models have not been developed for any formation, Sykes (1985, 1988) presented a detailed depositional model for both the New Brighton Conglomerate and the Morley Coal Measures based on work done in the northeastern part of the coalfield. Sykes' model was based on detailed descriptions of sections and faces in opencast mines and on limited outcrops. He also incorporated sandstone and coal petrology and geochemistry. Sykes compared vertical profiles of the New Brighton Conglomerate to published models and concluded that the New Brighton Conglomerate was the product of prograding alluvial fans. He also compared vertical profiles from the Morley Coal Measures to published models and deduced that Morley sediment accumulated in a braided river channel system and well drained floodplain. Sykes inferred that Morley peat deposition occurred in a poorly drained and densely forested backswamp area adjacent to the fluvial floodplain.

In addition to the models of Sykes, Bowman (1987) described a general model for accumulation of Beaumont sediments in the east of the coalfield. Bowman considered that Beaumont sedimentation was initiated by widespread lacustrine deposition followed by sandy fluvial deposition. A swampy lacustrine environment then reoccurred which was covered by a low energy fluvial system in the south of the area.

1.3 COALFIELD GEOLOGY

1.3.1 General Tectonic Setting During Coalfield Development

Ohai Coalfield, together with Greymouth, Pike River and Kaitangata Coalfields, developed during a time of extension in the New Zealand continental crust. It should be noted that although these three coal basins developed contemporaneously, each coalfield was subject to a different specific tectonic regime. The timing of coalfield basin development post-dates separation of New Zealand from Gondwana, which is thought to have been completed by 85 Ma (Bradshaw, 1989). The nature of the post-separation extensional regime, which resulted in rift basin development along the West Coast of New Zealand, is not clearly understood. Initial phases of sedimentation, in the late Cretaceous, were terrestrial. During the Paleocene, sedimentation at Ohai slowed or ceased although accumulation of sediments continued at Greymouth and Pike River on a very local scale, and at Kaitangata, where late Cretaceous to Paleocene transgression occurring on the east side of New Zealand periodically resulted in marine conditions. No Paleocene sediment has been found at Ohai. During the Eocene, fault systems (possibly pre-existing) within the coalfield basins were activated, resulting in further accumulation of non-marine sediments. The reactivation of fault systems is attributed to the development of a new rift system on the western edge of the Eocene New Zealand landmass (Kamp, 1986). Continuing extension throughout the Eocene and Oligocene resulted in submergence of most of the previously sub-aerial New Zealand landmass and widespread marine sedimentation occurred over the New Zealand continental crust. Ohai Coalfield probably developed 100 km northeast of the present West Coast coal basins such as Greymouth. However, as a result of dextral offset along the Alpine Fault system from Miocene times, Ohai is now approximately 450 km south and west of Greymouth Coalfield which developed coevally on what is now the western side of the Alpine Fault.

1.4.2 Regional Geology

Ohai Coalfield is a west-to-northwest trending fault-controlled depression unconformably underlain by Permian and Triassic-Jurassic basement (Fig. 1.3). The basement consists of Takitimu Group volcanics (Permian) in the west and Murihiku Supergroup volcanogenic sediments (Triassic-Jurassic) in the east. Within the depression is a succession of Cretaceous to Oligocene sediments with a local Quaternary cover. The basin reaches a maximum depth of 1500 m adjacent to the Twinlaw Fault which, together with its eastern extension, the Wairio Fault, forms the southern boundary of the coalfield.

Sediments thin from the southern to the northern margin of the basin which consists in part of a series of major northwest-southeast trending faults with a subordinate set of faults which trend northeast-southwest (Bowman et al., 1987). The northern boundary of the coalfield is considered to be part of a major fault zone forming the southwest boundary of the Takitimu Range (Mutch, 1972). Where sediments are not faulted the Cretaceous Wairio Coal Measures are seen directly overlying basement (Mutch, 1972). The Ohai Basin opens westward into the Waiau Basin, which developed as the result of Cretaceous-Tertiary movement on regional fault systems (Bowman et al., 1987); the Waiau Basin contains 3000-5000 m of Cretaceous and Tertiary sediment (Turnbull et al., 1989). To the east of Ohai Coalfield lies the Winton Basin in which over 1000 m of marine sediments accumulated during the Tertiary in a relatively stable tectonic environment (Bowman et al., 1987).

1.4.3 Coalfield Structure, Stratigraphy and Depositional Setting

1.4.3.1 Structure

The recent work by Bowman et al. (1987), Cave and Ross (1986) and Ross (1986a, b) indicates that the coalfield has a general half-graben structure deepening to the southwest, towards the Twinlaw Fault. Within the coalfield at least three subsidiary structural basins, the Ohai, Mossbank, and Nightcaps Basins, have been identified from drillhole intersections, seismic data and field mapping. These sub-basins controlled deposition of the Morley and Beaumont Coal Measures (Figs. 1.4, 1.5).

The dominant fault trend in Ohai Coalfield is northwest-southeast and northwest-trending faults occur along the northern boundary of the coalfield and within the coalfield; examples are the Fish Creek Fault Zone and the Railway Fault (Fig. 1.6). The Twinlaw Fault (Fig. 1.3) is the most significant single fault in the coalfield but runs east to west rather than trending northwest. The Twinlaw Fault is a major southwest-dipping reverse fault juxtaposing Permian Takitimu Group basement against the Cretaceous-Tertiary sediments of the Ohai Coalfield at the southern margin of the coalfield. At the western end of the Twinlaw Fault 1800 m net displacement has occurred (Woodward and Kicinski, 1983). Displacement on the fault decreases to 800 m in the east of the coalfield where the Twinlaw Fault bifurcates into the McClean and Wairio Faults. As well as the northwest trending faults, a set of northeast trending faults are also present in the coalfield, the most significant being the Morley Fault. The two fault sets, northwest-southeast and northeast-southwest trending, divide Ohai Coalfield into blocks. Movement on the fault-bounded blocks may have controlled sedimentation during the Cretaceous and Tertiary (Bowman et al., 1987). Folding of coalfield sediments is also thought to have been a response to fault block movement (Bowman et al., 1987). There is only one major fold in the coalfield, the Ohai Anticline which lies northwest of Ohai township (Fig. 1.3). This anticline plunges southwest at approximately 8°; the fold limbs dip at 10-15° and are cut by east-trending normal faults.

1.4.3.2 Stratigraphy

The development of the stratigraphic nomenclature used for the sediments of Ohai Coalfield has already been discussed; the current stratigraphy of Ohai Coalfield is shown in Figure 1.2. Because of the similarity of lithologies and lack of marker horizons in the basement only broad divisions of basement lithologies are made, into a Group and a Supergroup on the basis of age. In contrast, the Cretaceous-Tertiary sediments are divided into five formations based on general lithologic differences. All drillhole locations mentioned in the following paragraphs are shown in Figure 1.6.

The two types of basement in Ohai Coalfield, the Permian Takitimu Group and the Triassic-Jurassic Murihiku Supergroup, are laterally juxtaposed but are separated by a complex fault zone. The Takitimu Group forms basement in the west of the coalfield and comprises flows and pillow lavas, tuffs, breccias and volcanogenic sediments cut by sills (Mutch, 1972). Sparse fragments of the Permian fossil *Atomodesma* occur in Takitimu sediments. The Murihiku Supergroup forms the basement in the east and is composed of volcanogenic siltstone, sandstone and conglomerate (Mutch, 1972).

The five Cretaceous-Tertiary formations are placed within two groups, the Ohai and Nightcaps Groups, based on age and structural relationships to one another. The Ohai Group is of Cretaceous age and is divided into three formations (Fig 1.5): the Wairio Coal Measures, the New Brighton Conglomerate and the Morley Coal Measures. Although stratigraphic information on the Wairio Coal Measures is sparse, owing to lack of outcrop and drillhole intersections, Cave (1992) divided this formation into two members, the Swampy Creek Member and the Dail Member. The Swampy Creek Member unconformably overlies basement and consists of pebble to cobble sized conglomerate and breccia beds that are 10 cm to 1 m thick, together with rare sandstone and carbonaceous mudstone beds. Clast lithologies in the Swampy Creek Member include metamorphosed green lithic sandstone, green and red porphyritic volcanics, plagioclase-phyric andesite and rare schistose-mylonite. The Swampy Creek Member is conformably overlain by the Dail Member. The Dail Member is characterised by a generally fine-grained sequence of green lithic sandstone and siltstone, carbonaceous mudstone and coal, all of which occur in beds from 8 cm to over 2 m thick.

There are at present too few drillhole intersections in the Wairio Coal Measures to construct the three-dimensional geometry of the formation. However, it has been found that neither of the two Wairio Formation members is present in the west or north of the Ohai

Basin (in drillholes 338 and 339 in the west and drillhole 321 to the north) nor is either member present in the Nightcaps Basin. The maximum total thickness of Wairio Coal Measures drilled in the Ohai Basin is 53 m, in drillhole 334; in the Mossbank Basin the maximum total thickness of the formation intersected was 44 m, in drillhole 373.

The New Brighton Conglomerate rests conformably on the Wairio Coal Measures or directly on basement in areas where Wairio sediments are absent. The New Brighton Conglomerate mainly comprises granule to cobble, matrix supported conglomerate, although occasional clast supported pebble and granule beds occur. The coarser grained conglomerate is in beds with a wide range of thicknesses, from 20 cm to over 9 m, whereas the finer grained conglomerate beds are always less than 1 m thick. A wide variety of clast lithologies have been observed by both Bowman et al. (1987) and Cave (1992) including red silicic andesite (in the middle to lower part of the formation), grey granitoid, pink granite and biotite gneiss (dominant at the base of the formation but present throughout the formation), green sandstone, laminated siltstone, green hyaloclastite and volcanogenic breccia (common throughout the formation). Cave (1992) noted that clast angularity decreases upwards through the formation. Occasional medium to coarse grained sandstone beds occur which range in thickness from 40 cm to 3 m. These sandstone beds grade up into laminated siltstone or carbonaceous mudstone and sometimes into coal seams less than 1 m thick.

The New Brighton Conglomerate is present in the south of the Ohai Basin (a maximum thickness of 92 m of the formation has been recorded, in drillhole 343) but thins rapidly to the north where Morley Coal Measures directly overlie basement in drillhole 321. In the Mossbank Basin the New Brighton Conglomerate appears to be considerably thicker than in the Ohai Basin; 161 m of the formation was intersected in drillhole 373. Once again, in this sub-basin the New Brighton Conglomerate thins northwards and the entire Ohai Group is absent to the north and northeast of drillhole 373 where Eocene Nightcaps Group sediments directly overlie Murihiku basement.

The Morley Coal Measures conformably overlie the New Brighton Conglomerate and consists of three main lithologies, sandstone, mudstone and coal, with subordinate conglomerate, siltstone and claystone. Conglomerate beds are less than 1 m thick, are of varied clast size and texture and are most common in the lower part of the formation (Cave, 1992). Clast types include gneiss, gabbro/diorite, foliated green metasediment, pelitic schist, green volcanic breccia, green porphyritic and aphanitic volcanic clasts, fine grained siliceous material and rare granitic clasts. Sandstone beds range from a few centimetres to 25 m in thickness and are characteristically poorly sorted. Thick beds are either homogenous or display centimetre to metre scale cross-bedding. In thinner beds, coarse to medium sandstone typically displays planar or trough cross-bedding whereas fine or very fine sandstone is generally massive or flat to ripple laminated. Mudstone beds are generally thinner than sandstone beds and range from non-carbonaceous to highly carbonaceous. Coal seams in the Morley Coal Measures are from a few centimetres to 26 m thick, reaching maximum thicknesses in the southern parts of the Ohai and Mossbank Basins. Definition of coal seam stratigraphy in the Morley Coal Measures has remained problematic since Lillie's division of sediments into 4 coal horizons. In the Ohai Basin, Bowen (1964) recognised 6 seams within the Morley Coal Measures: the Morley No. 1, Morley No. 2, and Morley No. 3 seams basin-wide, and the Star, Couper, and Linton Main seams which were restricted to the northern end of the Ohai Basin. In addition, a seam worked in the Morley Mine is commonly referred to as No. 1.5. In the Mossbank Basin, Bowman et al. (1987) defined 6 seams: C, B4 through to B1 and A. Problems in the existing nomenclature stem from the fact that previous authors only named seams in restricted areas of the basins or gave single seam names to coal bodies which may have been contemporaneous but are separated by clastic sediment. Correlation of coal seams is considered in detail in Chapter 2 and a nomenclature suggested for the horizons in which seams occur rather than attempting to name individually each of the numerous seams within the coalfield.

Accumulation of Morley Coal Measure sediments occurred in at least three separate basins, the Ohai, Mossbank and Nightcaps Basins (Fig. 1.3). Between the Ohai and Mossbank Basins the Morley Coal Measures thin to 7 m (in drillhole 352) over the basement structure known as the Bluebottle High (Fig. 1.3). As well as being defined by drillhole data (displayed in Chapter 2), the Bluebottle High has been outlined by high resolution seismic surveying (Ross, 1986a). Between the Mossbank and Nightcaps Basins Morley Coal Measures are absent over the faulted basement structure named the Moretown High by Cave (1992). The Moretown High is defined by seismic surveys (Ross, 1986b) and drillhole intersections. The Nightcaps Basin appears to contain a condensed sequence of the Morley Coal Measures. The formation also thins both to the north and the west and is absent in drillholes 338 and 339. Morley Coal Measures are also absent in the far southeast of the coalfield (drillhole 881, Fig. 1.6). Cave (1992) suggested that this area was sub-aerially exposed during the Cretaceous. Although Morley sediment has not been correlated to any Cretaceous sediment outside the coalfield, Raine (1989) attributed a sediment sample from the Wairaki Hills north of Ohai Coalfield to the Cretaceous, based on palynology. This suggests that local areas of Cretaceous sediment may be preserved in the vicinity of the coalfield.

The Nightcaps Group is Eocene in age (Fig. 1.5) and consists of two formations, the Beaumont Coal Measures and the Orauea Mudstone. The Beaumont Coal Measures unconformably overlie the Morley Coal Measures. In the north of the coalfield the Cretaceous-Eocene unconformity is readily visible where it occurs above a prominent white leached layer. However, the unconformity rarely occurs in outcrop throughout most of the coalfield and cannot be identified visually in most drillcores, particularly drillcores from the south of the coalfield. The similarity of lithologies in the Beaumont and Morley Coal Measures precludes identification of the unconformity on a lithological basis, therefore in drillcore the Cretaceous-Tertiary transition can be reliably identified only by palynology (Warnes, 1990). The maximum discordance of 20° between Cretaceous and overlying strata occurs in the northeastern part of the coalfield, indicating considerable tectonic activity during the period between accumulation of the Ohai and Nightcaps Groups. Beaumont Coal Measures comprise sandstone, siltstone, mudstone (containing varying amounts of carbonaceous material) and coal. The coal seams are dirty, generally less than 2 m thick and contain macroscopic resin blebs up to 1 cm wide. Seams are discontinuous and because there is no basis for correlation no seam nomenclature is attempted. Overall, there are greater proportions of fine-grained clastic sediments in the Beaumont Coal Measures in the Morley Coal Measures.

Beaumont Coal Measures accumulated in at least two basins, the Ohai and Mossbank Basins (Fig. 1.5). Between the Ohai and Mossbank Basins, Beaumont sediments thin over the Bluebottle High to a minimum of 24 m, in drillhole 352. However, whereas Morley Coal Measures are absent over the Moretown High, the Beaumont Coal Measures are at their thickest in this area (85 m in drillhole 371). Beaumont sediments are generally thicker in the Ohai Basin than in the Mossbank Basin and attain a maximum thickness of 146 m in drillhole 362. The Beaumont Coal Measures extend westwards into the Waiau Basin and possible correlatives are recognised to the east in the Winton Basin (Cave, 1992).

Beaumont Coal Measures are conformably overlain by the Eocene Orauea Mudstone, which in turn has an inferred gradational contact with the overlying Waicoe Formation. Only minimum thicknesses of Orauea Mudstone are intersected within Ohai Coalfield because all drillholes were collared below the top of the formation. This formation comprises an unbedded, homogenous, dark grey mudstone. There is typically an increase in carbonaceous material within the basal 6 to 10 m of the formation.

The Orauea Mudstone reaches a maximum recorded thickness of 426 m, in drillhole 371, and appears to thicken towards the west, unlike trends in sediment thickness in all Cretaceous and older Tertiary sediments. Thicknesses in the west of more than 550 m are inferred on the basis of unpublished seismic data (Cave, 1992). The thickness of the Orauea Mudstone indicates that its development was not influenced by subsidiary basins within the coalfield and the absence of Orauea sediments over the Moretown High is thought to be related to late Cenozoic fault activity (Cave, 1992).

1.4 MINING HISTORY AND UTILISATION OF COAL

Mining at Ohai Coalfield has been carried out in two main areas, Ohai and Nightcaps (Fig. 1.1). At Ohai the rank of coal mined is sub-bituminous A whereas the rank at Nightcaps is sub-bituminous C. Most of the coal already mined has been taken from the Morley Coal Measures; only about 2% of total coal mined has come from the Beaumont Coal Measures, New Brighton Conglomerate or the Wairio Coal Measures.

The first mining in the Ohai area was undertaken by the Nightcaps Coal Co. in 1879. Opencast production at Nightcaps increased until 1914 when mines opened in the Ohai district but thereafter production at Nightcaps declined. Underground mining first began when the Wairaki Mine opened at Ohai in 1914. This mine was worked until 1971 when it was closed as the result of fire. A second underground mine, Morley Mine, opened in 1952 and worked coal from the "No. 2 Seam". However Morley Mine was forced by economic pressures to close in 1988. Another underground operation, Beaumont Mine, worked the "Couper Seam" from 1979 until 1984 by which time all available coal had been removed. In 1981 redevelopment of Wairaki Mine commenced and now Wairaki No. 6 is the only operational underground mine at Ohai, producing approximately 150 000 tonnes per year from the "No. 2 Seam". During the 1970s and early 1980s a number of opencast mines were excavated in the Ohai district: opencasts No. 3, No. 6, No. 16 and No. 16 extension. All Ohai opencasts are now abandoned and the only remaining opencast is at Nightcaps where sub-bituminous C coal is still mined on a small scale; the mine has an output of approximately 9 000 tonnes per year.

Before 1944 mining was undertaken by privately owned companies, the Mt. Linton, Wairaki and Nightcaps Coal companies. However after this time the Government (State Coal Mines) took over most of the coalfield and has since been the dominant producer although State Coal became a self-owned enterprise in 1989 and is now known as CoalCorp. Of the two remaining mines at the coalfield, CoalCorp runs the Wairaki No. 6 underground mine while the Nightcaps opencast is a private concern.

The nature of the coal and the splitting characteristics of coal seams creates mining difficulties at Ohai. An on-going problem is creation of fines (coal particles from 0.5 to 6 mm in diameter), which comprise up to 30% of total coal mined. Briquet (1986) concluded that the fines are produced mainly because of mechanised coal mining. Other South Island underground mines are unmechanised and do not produce significant quantities of fines. There is no ready market for the fines and their tendency to spontaneous combustion means underwater storage is necessary. The structural complexity, difficulty in seam correlation, lack of widespread marker horizons and sparsity of outcrop in the coalfield have prevented construction of a three-dimensional model for coal and sediments, which in turn has limited mine planning. Coal produced at Ohai is largely for the domestic and industrial market in Southland, as transport of the coal is uneconomic. The rank of the coal precludes its utilisation for coke production and the coal is used for heating purposes.

1.5 THESIS SCOPE AND OBJECTIVES

The aim of this project was to integrate information from several geologic disciplines, that is, sedimentology, coal chemistry, coal petrology and palynology, in order to delineate the environments in which the Morley Coal Measures (Cretaceous) and Beaumont Coal Measures (Eocene) were deposited and, if possible, to determine the geological controls on these environments. Recent studies on the geology of Ohai Coalfield have generally focussed on small areas within the coalfield or on particular aspects related to the industrial significance of the coal seams. Some studies have assessed the stratigraphic framework of the basin using a variety of techniques such as lithostratigraphy, seismic stratigraphy and palynology. However, coalfield-wide integration of the various types of information has not previously been attempted.

A general research objective was to develop models for the depositional environments of the Morley and Beaumont Coal Measures as no pre-existing models incorporate the whole of Ohai Coalfield. Although a model for the Morley Coal Measures coalfield-wide was designed by Sykes (1985), this model was based on data in only a small portion of the coalfield. The only existing model for the Beaumont Coal Measures is a broad coverage of Beaumont sedimentation in only the Mossbank Basin (Bowman, 1987). An area of major interest in modern coal research is determination of the effects of contemporaneous clastic sedimentation on paleomire environments. Therefore a specific sedimentological research objective was to define the sedimentary environments present during accumulation of the coal measures and to assess whether deposition of peat and sediments occurred contemporaneously. Chemical and petrological analysis of coal was undertaken in order to examine temporal and spatial variations in coal properties which could be related to changes in the depositional environment of the peat. Both composite and ply samples of coal were analysed so that the scale of variation in coal properties both between and within seams could be observed. In addition the palynology of Morley and Beaumont coal was concurrently examined by another worker so that palynological data could be integrated with other coal data. The objective of the palynological work was to to investigate successional changes in the floral community of the mires and to examine differences between the floral assemblages of mires and associated clastic sedimentary environments. Another aim of palynological analysis was to identify possible relationships between changes in the assemblage of peat-forming flora and variations in coal chemistry or petrology.

The area of study was originally intended to encompass the whole of Ohai Coalfield. However, it soon became apparent that data on sediments and coal were available only in the northern and eastern parts of the coalfield area. Outcrop is very sparse throughout the coalfield and only two opencast mine faces, which are in the northeastern sector of the coalfield, can be utilised for observation of sediments. Drilling has been carried out only in the northern half of the coalfield because overburden thicknesses in the southern part of the coalfield are to great for extraction of coal to be economic at present. Nevertheless, as far as possible, sedimentological interpretations have been extrapolated to the part of the coalfield for which there are no data at present.

CHAPTER 2

BASIN ANALYSIS AND LITHOSTRATIGRAPHY OF THE MORLEY AND BEAUMONT COAL MEASURES

2.1 INTRODUCTION

Reconstruction of the paleoenvironments in which coal-bearing sediments have been deposited requires synthesis of data from both coal and inorganic sediments. To determine the depositional relationships between coal and clastic sediments, the vertical and lateral variations of all lithologies must be delineated. In addition, the scale at which sediments vary should be assessed. The approach employed in any paleoenvironmental study will depend on how much subsurface information is available and on the scale and quality of any outcrop. The type of paleoenvironmental model which can be formulated and the amount of detail in such a model are contingent on the amount and type of data which can be obtained.

Models of fluvial systems are frequently used to assist reconstruction of mire paleoenvironments. Fluvial depositional models are generally classified according to the appearance of the fluvial systems in plan view, that is, fluvial planform. Such models are of limited geological value because 1) most characteristics of fluvial systems which are preserved in the rock record are not diagnostic of any particular fluvial planform and 2) sedimentary features which may be diagnostic of particular planforms can be observed only in large, three-dimensional outcrops, and not in drill core or mine faces. However, certain features of channels, such as stability, can be deduced from sedimentary sequences without recourse to detailed facies models.

Varied mechanisms have been proposed to explain how clean peat, with the potential to form low ash coal, can accumulate. Peat may develop in an environment where very little clastic sedimentation is occurring. Alternatively, peat accumulation may be contemporaneous with active clastic sedimentation but the sediment may be prevented from reaching the peat. Doming of mires is one mechanism which restricts influx of sediment into peat, because the peat surface is raised above the usual level of fluvial channels. Peat developing on abandoned channel sandstone belts may also be physically isolated from sediment input. Another model for clean peat accumulation is a stable channel fluvial system in which channels remain confined between levees which prevent sediment being transported into adjacent peat bodies.

Within Ohai Coalfield there are various sources of sedimentological information for coal-bearing formations, the Cretaceous Morley Coal Measures and the Eocene Beaumont Coal Measures. Sources of information include drill core, seismic line and gravity data and outcrop in the form of opencast and underground mines. The purpose of this chapter is to use this information to interpret the characteristics of clastic sedimentation in the Morley and Beaumont Coal Measures and to evaluate the mechanism(s) by which areas of peat accumulation were isolated from clastic input.

2.2 METHODS

Five types of data are used here for interpretation of the characteristics of clastic sediments and coal in the Morley and Beaumont Coal Measures:

1) Measured descriptive sections in two opencast mines (performed by the author, Figs 2.1 to 2.6).
2) General descriptions of lithologies in 92 drillholes. In the Ohai Basin the Morley Coal Measures was usually cored while other formations were logged from geophysical data and chips. Most drill holes in the Mossbank Basin were cored through both the Morley and Beaumont Coal Measures.
3) Detailed examinations of portions of over forty drill cores (used to assess the accuracy of drill core logs).
4) Previously described mine sections (underground and opencast) of Sykes (1985).
5) Previously published seismic and gravity data (Woodward and Kicinski, 1983; Cave and Ross, 1985, 1986; Ross, 1986a, b).

Mine sections were measured for this thesis to investigate whether specific lithologic horizons could be correlated in areas of good exposure. It was important to determine whether lithologic units could be defined and correlated at outcrop scale, in order to assess the validity of correlations between drillholes several hundreds of metres apart. In addition, the variability of small scale sedimentary structures and grain size can indicate the original variability of sedimentary processes.

Correlations were made between mine sections from Sykes (1985) and drill core logs. Correlation of sediments was hindered by the lack of any key stratigraphic horizons and by the similarity of sediments in the Morley and Beaumont Coal Measures. Delineation of the bounding surface between the coal measures was assisted by palynology (Warnes, 1988; Raine, 1989; Ward, 1990). The criteria used to correlate between individual drill logs are set out in Appendix A. Thirty-two cross-sections, 16 from each formation, were constructed to aid correlations throughout the coalfield. Then 5 composite sections, representative of the whole coalfield, were drawn for each of the Morley (Fig.s 2.7 to 2.12) and Beaumont Coal Measures (Fig.s 2.13 to 2.18). It must be pointed out that the horizontal scales in these cross-sections are approximate. In addition, the sections do not always follow straight paths as sections had to be drawn along lines where drillhole data was available.

The sedimentary relationships between the formations in Figures 2.8 to 2.13 are variable. The nature of the basal contact of the Morley Coal Measures is not always known. In some locations, the coal measure sediments have a gradational contact with the underlying New Brighton Conglomerate whereas in other locations, particularly towards the sub-basin margins, the contact is probably faulted. The Morley and Beaumont Coal Measures is unconformable in some areas but may be conformable in others, particularly in the south of the coalfield. Although there is no clear palynological evidence of Paleocene age flora to date, the location of the unconformity surface is impossible to recognise visually in most drill core, suggesting that little erosion or weathering of the surface occurred. The top of the Beaumont Formation in Figures 2.14 to 2.18 is shown interfingering with the overlying Orauea Mudstone because the contact between these two formations is probably diachronous.

Drill core logs, mine sections and cross-sections all assisted in creation of isoline maps for total sediment thickness, total thickness of coal, thickness of individual coal seams or coally horizons and the ratio of fine- to coarse-grained sediment in both coal measure formations (thicknesses of formations and lithologies within formations are reported in Appendix B). This information together with seismic (Cave and Ross, 1985, 1986; Ross, 1986a, b) and gravity data (Woodward and Kicinski, 1983) was used in reconstruction of sub-basin geometries. Logs and cross-sections were also used to reconstruct the geometry of large scale sedimentary units (hundreds of metres in lateral extent).

2.3 RESULTS

Drill core and mine faces are composed of four general lithologies:

1) Sandstone, always poorly sorted with the maximum grain size ranging from very fine to very coarse.
2) Mudstone.
3) Carbonaceous mudstone, containing varying quantities of carbonaceous material.
4) Coal.

The character of each of lithology is described and the distribution of lithologies in both the Morley and Beaumont Coal Measures is compared at outcrop and basin scale.

2.3.1 Description of Lithological Units at Outcrop scale - Opencasts Nos. 6 and 16

In Opencasts Nos. 6 and 16 (for locations see Fig. 1.1), only the upper part of the Morley Coal Measures and the lower part of the Beaumont Coal Measures are exposed. In Figures 2.1 and 2.2 measured sections in each mine face are correlated, showing the two-dimensional geometry of exposed lithologic units. Locations of the sections in the mines are displayed in Figures 2.3 and 2.4. The opencasts have been previously described by Sykes (1985). The description of the Morley Coal Measures given here is similar to that of Sykes. However, he did not discuss the lithologies in the Beaumont Coal Measures in detail.

2.3.1.1 Morley Coal Measures

Although the Morley Coal Measures comprise similar lithologies in both opencasts the sedimentary beds display different lateral and vertical relationships to one another. These relationships can be summarised by grouping vertical sequences of sedimentary beds, which are generally bounded by erosional surfaces, on the basis of variation in grain size. Four general groups, or associations, of lithologies can be distinguished in the Morley Coal Measures sediments:

1) Stacked sandstone beds ('S'-association).
2) Interbedded sandstone and mudstone, in fining-upward sequences ('SF'-association).
3) Thinly interbedded mudstone and fine-grained sandstone ('F'-association).
4) Carbonaceous mudstone beds and coal seams ('C'-association).

Associations 1, 2 and 3 are all commonly both laterally and vertically adjacent to one-another but association 4 is nearly always only vertically adjacent to other associations. Although individual beds within associations are of limited lateral extent, associations themselves can be easily traced in outcrop across the opencast faces (as shown in Figs. 2.1, 2.2. and 2.4) and therefore are useful units for correlation at mine-face outcrop scale.

The above division of the Morley Coal Measures into associations differs from that suggested by Sykes (1985). He only described two associations, a sandstone - mixed association in both opencasts and a sandstone - mudstone association in No. 6 Opencast. Sykes included coal and highly carbonaceous sediments in his two sedimentary associations whereas in this thesis coal and associated carbonaceous mudstone are considered to form a separate sedimentary package on the basis of their continuity as compared to that of other sedimentary units.

<u>'S'-association</u> units are present across the southern face of Opencast No. 16 and in the southern part and at the base of the northern part of the west face of Opencast No. 6. These units have lenticular two-dimensional morphology, 2 m to 10 m thick and 10 m to 15 m wide. The lowest sandstone bed in the 'S'-units usually has an erosive base (Fig. 2.5 (a)), often with a lag of mudstone rip-up clasts. The bases of the units generally become less erosive towards the unit margins. The central beds in the units exhibit planar (Fig. 2.5 (a)) or trough cross-bedding (Fig. 2.5 (b)) whereas graded beds (Fig. 2.5 (b)) occur at the margins of the units. Sandstone in the 'S'-association is poorly sorted. Coarse- to fine-grained sandstone sometimes grade up into medium to fine-grained and then fine-grained

sandstone; the finer grained beds are massive, flat laminated or ripple laminated (Fig. 2.5 (c)). Rooting is common in many of the finer grained sandstone units.

'SF' association units (sections 1 and 2 in Fig. 2.6 (a)) occur only in the northern part of Opencast No. 6. 'SF' units have trough-shaped basal erosion surfaces (Fig. 2.6 (a)), are 1 m to 3 m thick and 5 m to 10 m metres wide. All 'SF' units fine upwards from poorly sorted medium to fine-grained sandstone into fine-grained sandstone and then into mudstone, which may contain carbonaceous material. Medium to fine-grained sandstone beds display trough cross-bedding and fine sandstone beds are flat to ripple laminated. The beds at the bases of the 'SF' units often contain pebble-size mudstone clasts and lenses of coarse-grained sandstone.

A single 'F'-association unit occurs, at the top of the Cretaceous sequence in Opencast No. 6. (Figs. 2.1 and 2.6 (a)). This unit is 3-7 m thick and is composed of interbedded fine-grained sandstone (10 - 60 cm massive or flat-laminated beds) and mudstone (10 cm - 3 m beds).

A number of 'C' association units occur in the No.16 Opencast (Figs. 2.2 and 2.4) but only two such units are seen in the No. 6 Opencast, at the base of the sections (Fig. 2.1). 'C'-association units are from 20 cm to over 4 m thick and at least 500 m wide. 'C'-association units are composed of clean bright-banded coal, dirty coal, carbonaceous mudstone which is often rooted and occasional beds of very fine-grained sandstone. The bases of coal seams are in gradational contact with the underlying carbonaceous mudstone. A similar transition into rooted carbonaceous mudstone sometimes occurs at the top of coal seams, otherwise coal is directly overlain by an 'S'-association unit with an erosive base. Carbonaceous mudstone may grade vertically into very fine sandstone. In the No. 16 Opencast, most 'C'-association units thin westwards and grade into mudstone and fine sandstone. The area at the west end of the opencast may have remained a locus of channel deposition throughout accumulation of both 'C'- and 'S'-association units.

2.3.1.2 Beaumont Coal Measures

The surface between Morley and Beaumont sediments is generally regarded as an unconformity based predominantly on pollen assemblages (see Chapter 1). The unconformity can be easily recognised in both the No. 6 and No. 16 Opencasts where distinctive lithologies lie above or below the unconformity surface. In Opencast No. 6 a thin sandstone horizon lies at the base of the Beaumont Coal Measures (Fig. 2.1) and forms a prominent marker; no significant erosion or weathering is visible in the underlying Cretaceous sediments. In contrast, sediments below the unconformity in Opencast No. 16 appear severely leached (white and friable) and the unconformity surface is clearly erosional

(Fig. 2.4), truncating underlying Cretaceous beds. Further evidence of weathering in No. 16 is the composition of Cretaceous sandstones directly below the unconformity; the feldspar and smectite in these sandstones have been altered to kaolinite (Sykes, 1985). It is interesting that the unconformity in No. 16 is most eroded in the area where coal seams pass laterally into low energy channel deposits; this area may have remained a locus of channel activity both during and following Morley sediment deposition.

Beaumont sediments in the two opencasts display less variable spatial relationships than the Morley sediments. Only two general associations of beds (based on variations in grain size in a vertical sequence) can be distinguished:

1) vertically stacked sandstone beds with little fine sediment ('S'-association)
2) interbedded fine sandstone, mudstone, carbonaceous mudstone and coal ('F'-association).

The 'S'- and 'F'-associations occur vertically stacked and are not laterally adjacent to one another at the scale of the opencasts.

<u>'S'-association</u> units can be traced along the length of each opencast (Figs. 2.1 and 2.2) and are therefore at least 500 m in extent. The three 'S'-association units in Opencast No. 6 are 2 m to 4 m thick while the 2 units in No. 16 are 3 m and 10 m thick respectively. S-association units are mainly composed of poorly sorted, coarse- to fine-grained sandstone. The sandstone beds usually have basal erosive surfaces with a lag of mudstone or carbonaceous mudstone clasts (usually pebble-sized but up to 1 m across) as pictured in Figure 2.6 (b). The coarse- to fine-grained sandstone exhibits large scale planar cross-bedding (Fig. 2.6 (c)). These sandstone beds occasionally fine upwards into flat to ripple laminated medium-fine and fine sandstone, mudstone, carbonaceous mudstone and coal. In Opencast No. 6 it is evident that finer-grained sediments accumulated but were later eroded locally during deposition of the overlying coarse-grained sandstone bed.

In both opencasts a single <u>'F'-association</u> unit occurs, at the base of the Eocene sequence. The 'F'-association units can be traced across the opencast faces (Figs. 2.1 and 2.2), a distance of approximately 500 m. In No. 16 the 'F'-unit is 10 to 14 m thick, increasing to a maximum where erosion on the Cretaceous-Tertiary boundary was greatest (Fig. 2.4). In No. 6 the 'F'-association unit varies in thickness from 4 to 7 m, increasing in thickness towards the north. The sandstone in 'F'-units is flat to ripple laminated, the carbonaceous mudstone often displays rooting (Fig. 2.6 (d)) and the coal is generally dirty. Coal seams vary in extent from 100 m to 500 m where it is possible to trace them laterally. Both mudstone and carbonaceous mudstone beds contain <u>*Velesunio huttonii*</u> (a Tertiary freshwater bivalve).

2.3.2 Description of Lithological Units at Basin Scale

With the exception of coal seams, individual beds cannot generally be correlated between drillholes which are spaced too widely in comparison to the scale of bedding Drillholes are 500 m to 1000 m apart whereas clastic beds extend 3 m to 15 m, as seen in the opencast mine faces. In contrast, coal seams extend 500 m in the opencast faces and up to 1.5 km in the Wairaki No. 6 underground mine. However, although individual clastic beds are not correlatable, units which are dominantly composed of any one of the four main lithologies occurring in the coal measures (sandstone, mudstone, carbonaceous mudstone, coal) can be correlated from one drillhole to the next. Ten composite cross-sections (Figs. 2.7 to 2.18) show the correlation of lithological units between drillholes in the Ohai and Mossbank Basins at Ohai Coalfield.

The shapes of sandstone and coal units in the Morley and Beaumont Coal Measures, and of carbonaceous mudstone units in the Beaumont Coal Measures, are described below. The shapes of mudstone units are not described because they form a complementary 'background' for the sandstone, coal and carbonaceous mudstone horizons. The shapes of carbonaceous units in the Morley Coal Measures are not described because they are related to the shapes of the coal units.

2.3.2.1 Morley Coal Measures

In the Morley Coal Measures, thickness and lateral extent define four types of sandstone body (Table 2.1):

1) Sandstone sheet: 2 m to 10 m thick, 0.8 km to 2.0 km by 1.0 km to 3.0 km lateral extent.
2) Composite sandstone sheet: 15 m to 25 m thick, 1.0 km to 1.8 km lateral extent.
3) Sandstone ribbon: 30 m thick, 0.6 km to 0.8 km by 3 km to (?) 9 km lateral extent.
4) 'Thin' sandstone sheet: 2 m to 5 m thick, 0.8 km to 2.5 km by up to 7 km lateral extent.

The first three sandstone body types occur in only the Ohai Basin while the fourth type is present only in the Mossbank Basin. Examples of the sandstone body types are labelled in Figures 2.8, 2.10 and 2.11.

The 'thin' sandstone sheets found in the Mossbank Basin are typically less than 5 m thick, have and can be correlated throughout most of this sub-basin (7 km in the largest dimension). In contrast, the sandstone sheets in the Ohai Basin, although sometimes thicker (up to 10 m), cannot be correlated across the sub-basin. The second sandstone body type in the Ohai Basin is the composite sandstone sheet comprising sandstone sheets which are stacked vertically. Sandstone ribbons, the third sandstone body type in the Ohai Basin, are generally 30 m thick and 600 m to 800 m wide in cross-section. Sandstone ribbons are elongate approximately parallel to the Ohai Basin axis and may be as much as 9 km in length, although the full length of the sandstone ribbons cannot be at present ascertained due to the absence of drill hole data in the southern part of the sub-basin.

Coal seams in the Morley Coal Measures are up to 26 m thick. Thickness and lateral extent define two coal body types (Table 2.2) in the Ohai and Mossbank Basins:
1) 'Large' coal sheet: 8 m to 26 m thick, 1 km to 3 km by 1 km to 3 km lateral extent.
2) 'Small' coal sheet: 5 m to 10 m thick, 0.4 km to 2 km by 0.5 km to 1 km lateral extent.
Examples of the coal body morphologies are labelled in Figures 2.8, 2.10 and 2.11. The dimensions given for the coal bodies encompass measurements of all bodies present in the cross-sections. Although there may be some coal bodies that are intermediate in measurement, the majority of the coal bodies do fall into one general visual category or the other (that is, large or small). Nomenclature of individual coal bodies is not attempted (as already discussed in Chapter 1) because of the number of seams in the coalfield.

'Large' coal sheets are from 2 m to 8 m thick in the Mossbank Basin and the northern part of the Ohai Basin but thicken southwards in the Ohai Basin to 10 m to 26 m. Parallel to sub-basin axes (approximately northeast-southwest), large coal sheets are over 1 km in lateral extent and perpendicular to sub-basin axes (approximately northwest-southeast) they vary from 1 km to 3 km. Five 'large' coal sheets can be identified in each of the sub-basins. In the Mossbank Basin these coal sheets are vertically and horizontally adjacent to carbonaceous mudstone. In the Ohai Basin, 'large' coal sheets are laterally adjacent to mudstone or carbonaceous mudstone and are either vertically adjacent to carbonaceous mudstone or are overlain by sandstone.

'Small' coal sheets are generally thinner than 'large' coal sheets (5 - 10 m thick) and have smaller lateral dimensions (typically 1 km wide parallel and 0.5 km perpendicular to sub-basin axes). 'Small' coal sheets may be adjacent to either carbonaceous mudstone or sandstone at their margins and are far more common in the Ohai Basin than in the Mossbank Basin.

2.3.2.2 Beaumont Coal Measures

The Beaumont Coal Measures contain sandstone units which are similar in morphology to the Morley sandstone units. In the Beaumont Coal Measures two sandstone body types can be differentiated on the basis of thickness and lateral extent (their dimensions are shown for each sub-basin in Table 2.1):
1) 'Large' sandstone sheet: 6 m to 20 m thick, 2 km to 4 km by 2 km to 5 km lateral extent in the Ohai Basin, 5 km to 6 km by 9 km in the Mossbank Basin.

2) 'Small' sandstone sheet: 3 m to 12 m thick, 0.5 km to 4 km by 1 km to 2 km lateral extent.

The above sandstone body types are found in both the Ohai and Mossbank Basins and examples are labelled in Figures 2.14, 2.16 and 2.18. Once again, although the possibility of sheets intermediate to these sizes is not excluded, most sandstone sheets appear to be either laterally extensive or relatively small. Differentiation of sandstone body types is more difficult in the Ohai than the Mossbank Basin.

The 'large' sandstone sheets are up to 25 m thick. The single large sheet in the Ohai Basin has a maximum lateral dimension of 5 km whereas the 2 large sheets in the Mossbank Basin are more extensive, that is, up to 9 km in width. Although the 'large' sandstone sheets extend over much of the sub-basin in which they occur, some lateral interfingering of sandstone with mudstone and carbonaceous mudstone occurs.

The second sandstone body type is 'small' sandstone sheets, which are thinner (3 - 12 m) and have smaller lateral dimensions than 'large' sandstone sheets. 'Small' sandstone sheets in the Mossbank Basin (maximum width 4 km) are generally larger than those in the Ohai Basin (maximum width 2 km) although there are many more 'small' sandstone sheets in the Ohai Basin.

The coal seams in the Beaumont Coal Measures are thinner and contain more mineral matter than seams in the Morley Coal Measures. In addition, coal constitutes a smaller proportion of the total sediments in the Beaumont than in the Morley Coal Measures. The Beaumont Coal Measures contain only 'small' coal sheets (Table 2.2) which are difficult to correlate between drillholes. Two types of carbonaceous mudstone body occur in the Beaumont Coal Measures (Table 2.2):

1) 'Large' carbonaceous mudstone sheets: 10 m to 15 m thick, 1 km to 5 km by 4 km to 6 km lateral extent.
2) 'Small' carbonaceous mudstone sheets: 2 m to 15 m thick, 1 km by 1 km to 2 km.

The Mossbank Basin contains mainly 'large' carbonaceous mudstone sheets whereas most carbonaceous mudstone in the Ohai Basin is in 'small' sheets. Examples of carbonaceous mudstone body types are labelled in Figures 2.14, 2.16 and 2.18. The major difference between the two carbonaceous mudstone body types is in their lateral dimensions. 'Large' carbonaceous mudstone sheets generally cover an area of 12 km^2 to 30 km^2 whereas 'small' carbonaceous mudstone sheets cover a maximum area of 4 km^2. Both types of carbonaceous mudstone bodies are of highly variable thickness.

'Small' coal sheets in the Beaumont Coal Measures are 1 m to 4 m thick and are generally thinner in the Mossbank Basin than in the Ohai Basin. The coal generally occurs towards the top of carbonaceous mudstone units and the 'small coal sheets' have lateral margins adjacent to carbonaceous mudstone. The coal seams are sometimes also overlain by mudstone but are more commonly overlain by sandstone.

2.3.3 Distribution of Sediments Within the Ohai and Mossbank Basins

Integration of drill core, seismic and gravity data allow interpretation of the shapes of the sub-basins in which the Morley and Beaumont Coal Measures were deposited. The approximate plan views of these sub-basins (Ohai and Mossbank Basins) are shown in Figures 1.4 and 1.5. The axes of both sub-basins were oriented north-northeast during deposition of the Morley Coal Measures whereas during deposition of the Beaumont Coal Measures the axis of the Ohai Basin was oriented north-northeast but that of the Mossbank Basin was oriented northwest. In both the Morley and Beaumont Coal Measures, sediment in the Mossbank Basin is thinner than in the Ohai Basin (Figs. 2.8 to 2.12 and 2.14 to 2.18).

The distribution of sandstone, carbonaceous mudstone and/or coal bodies are described below for the Morley and Beaumont Coal Measures in both the sub-basins. Figures 2.19 to 2.22 (Morley Coal Measures) and Figures 2.23 to 2.25 (Beaumont Coal Measures) display isoliths of total sediment thickness, total coal thickness, the ratio of fine- to coarse-grained sediment and distribution of individual coal seams. Sediment distribution throughout the sequence is shown in the composite cross-sections (Figs. 2.7 to 2.18). In addition, the areal distribution of lithologies, for what are interpreted from the composite cross-sections to be synchronous sub-basin wide time intervals, are shown in Figures 2.27 to 2.30.

2.3.3.1 Morley Coal Measures

Total Morley sediment thicknesses (Fig. 2.19) are minimum values, as unknown thicknesses of the Morley sequence were eroded prior to and also possibly during early Beaumont deposition. Therefore it cannot be ascertained whether the sediment thickness distribution closely parallels the original sub-basin shapes. In the Ohai Basin total sediment thickness increases northeast to southwest, which is to be expected from the shape of the Ohai Coalfield half-graben. In addition, the sediment thicknesses generally increase from the sub-basin margins towards the centre and also close in towards the south end of the sub-basin. Total coal thickness (Fig. 2.20) and the ratio of fine- to coarse-grained sediment (Fig. 2.22) in the Morley Coal Measures increase in a similar way to total sediment thickness, from northeast to southwest within the sub-basins and also from the margins to the axes of the sub-basins, except for the southern margin. Figure 2.21 shows that thick coal beds containing <50% carbonaceous mudstone partings are more limited in lateral extent in the Ohai than in the Mossbank Basin although total thicknesses of coal are greater in the Ohai Basin. The most laterally extensive coal seams in the Ohai Basin are in the southern part of the area that has been drilled. Plan views show that coal seams do not directly overlap, indicating that mires developed at different times formed in different parts of the sub-basins.

The Morley Coal Measures sequence can be divided, on the basis of lithology, into 8 horizons in the Ohai Basin (O/C1, O/S1, O/C2, O/S2, O/C3, O/S3, O/C4, O/S4) and 4 horizons in the Mossbank Basin (M/C1, M/S1, M/C2, M/S2) as shown in Figures 2.8 to 2.12. Horizon M/C2 can be further divided into 4 sub-horizons, M/C2a, M/C2b, M/C2c and M/C2d. The horizons have been designated 'S', sand-dominated, or 'C', carbonaceous mudstone/coal dominated. The distribution of the sediment body types described in 2.3.2.1 are related to both these 'S'- and 'C'-horizons (Table 2.3) as well as to the shape of the Ohai Basin.

The three types of Morley sandstone body in the Ohai Basin occur in different parts of the sub-basin and in different horizons in the sequence. Sandstone sheets occur most frequently in horizon O/S4, at the top of the Morley sequence, and in the northeast of 'S'-horizons in the Ohai Basin. In contrast sandstone ribbons, which occur only in 'S'-horizons, are common in the southwest of Ohai Basin and along the sub-basin axis, but also occur in the northeast of Ohai Basin, in O/S3 and O/S2. 'Composite' sandstone sheets occur in all Ohai horizons but only near the present basin margin in the north, and also in the east, near the Bluebottle High. The Mossbank Basin contains only 'thin' sandstone sheets, which occur sub-basin wide in horizons Mossbank S1 and S2.

Coal body types also have particular distributions within the sub-basins. 'Large' coal sheets occur throughout both the Ohai and Mossbank Basins but only in 'C'-horizons. 'Small' coal sheets occur in the northeast of the Ohai Basin in both 'S'- and 'C'-horizons except in O/S4 in which they occur in all parts of this sub-basin. 'Small coal sheets' are also present in M/C2, as well as 'large' coal sheets.

The areal distribution of lithologies are plotted for time slices near the base of horizon O/S3 (Fig. 2.27) and tops of horizons O/C4 and M/C2d (Fig. 2.28). Figure 2.27 is drawn on the basis that the top of the 'large' coal sheets in O/C3 are time planes and therefore the immediately overlying sediment approximately represents a single time interval. Figure 2.28 is drawn on the basis that the top of the 'large' coal sheet in O/C4 is a time plane as are the tops of the two coal sheets in M/C2. The two horizons, in the different sub-basins, may be time-equivalent. In the sand-dominated interval, O/S3, sandstone is widespread but areas of mudstone and carbonaceous mudstone are present, particularly at the sub-basin margins. In the coal-dominated time slice (O/C4 and M/C2d), there are three coal bodies separated by mudstone and carbonaceous mudstone.

2.3.3.2 Beaumont Coal Measures

Sediment distributions in the Beaumont Coal Measures differ from those in the Morley Coal Measures. Total Beaumont sediment thicknesses (Fig. 2.23) and total coal thicknesses (Fig. 2.24) vary in the same way as the Morley Coal Measures in the Mossbank Basin but not in the Ohai Basin. Total coal thicknesses are greatest in the centre of the Mossbank Basin and in the south and at the northeast edge of the Ohai Basin. Variations in the ratio of fine- to coarse-grained sediment (Fig. 2.25) do not parallel the distribution of coal; in the Ohai Basin thicker coal generally occurs where the ratio is highest but in the Mossbank Basin the total thickness of coal is greatest adjacent to the area where the the greatest proportions of fine sediment occur. Coal-rich horizons (which contain numerous thin coal seams) in the Beaumont Coal Measures are laterally extensive, particularly in the Mossbank Basin. In both sub-basins the plan views of the 3 coal-rich horizons (Fig. 2.26) overlap, that is, mires developed at different times occupied the same parts of the sub-basins.

The Beaumont Coal Measures can be divided, on the basis of lithology, into 4 horizons in the Ohai Basin (O/C1, O/S, O/C-S, O/C2) and 5 horizons in the Mossbank Basin (M/C1, M/S1, M/C2, M/S2, M/C3) as shown in Figures 2.14 to 2.18. The distribution of sediment bodies described in Section 2.3.2.2, can be related to these lithological horizons (Table 2.3). 'Large' sandstone sheets occur only in S-horizons and 'large' carbonaceous mudstone sheets occur only in C-horizons. 'Small' sandstone sheets occur mainly in C-horizons and 'small' carbonaceous mudstone sheets are generally confined to the C-S horizon in the Ohai Basin. The only relationship between sediment body type and sub-basin shape is that, in O/S, the 'large' sandstone sheet is thickest in the west and north of the Ohai Basin.

In Figures 2.29 and 2.30 the areal distribution of lithologies is plotted for two time slices through the Beaumont Coal Measures. The time slices are through the top of O/S and M/S1 (Fig. 2.29), as well as O/C-S and the top of the contemporaneous M/C2 and M/S2 horizons (Fig. 2.30). Figure 2.29 assumes that the cessation of sand deposition in O/S and M/S1 was relatively synchronous. Figure 2.30 is a more tentative correlation, following the top of the thick carbonaceous mudstone unit in M/C2 and extending this correlation into the Ohai Basin. The correlation of sediments between the two sub-basins is uncertain in both figures therefore time slices may only be correlative within sub-basins.

In the 'S'-horizon time slice (O/S and M/S1) sandstone covers much of the Ohai and Mossbank Basins; localised mudstone deposits occur, but only in the Ohai Basin. In the slice through M/C2 and M/S2, carbonaceous mudstone is present in the north of the Mossbank Basin (M/C2) and sandstone is present in the south (M/S2); these relationships can also be seen in cross-section A, Fig. 2.14. In contrast, in the time-equivalent O/C-S horizon, mudstone is present throughout much of the Ohai Basin although areas of coal, carbonaceous mudstone and sandstone occur.

2.4 DISCUSSION

Interpretation of paleodepositional settings requires development of models for the sedimentary processes which occurred in a basin. Sedimentary models are usually designed with reference to pre-existing facies models. Recourse to facies models is desirable so that researchers have a framework with which they can compare their data (see the definition of facies models summarised by Walker (1984)). However, during the initial stages of interpretation of clastic sediments and coal at Ohai Coalfield it appeared that existing facies models were not useful frameworks from which to refine a model, or models, for Ohai Coalfield. In the following section the limitations of existing facies models, and the types of data these models require for interpretation of original depositional setting, are discussed with reference to data available at Ohai Coalfield. Finally, the conclusions on depositional setting that can be drawn for the Morley and Beaumont Coal Measures are outlined.

2.4.1 Limitations Affecting the Development of a Fluvial Model

At Ohai Coalfield there are three types of data available for comparison with facies models:

1) the vertical sequence of lithologies in individual drill cores
2) outcrop data, which includes vertical and lateral variation of sequences in mine faces
3) correlated drill core data, which provides information on the geometry of lithological units and the basin-wide variations in the distribution of these units.

These sediments were deposited in a half-graben within which some form of drainage system must have occurred. However, despite extensive drillhole data, there is insufficient information to develop traditional fluvial paleoenvironmental models for the Morley and Beaumont Coal Measures. The difficulty arises from the types and detailed nature of information required to recognise existing fluvial facies models. Each type of data listed above has limitations which restrict its application to depositional modelling.

2.4.1.1 Limitations of Data From Individual Drill Cores

Drill cores provide essentially one-dimensional information on sediments, that is, data on the vertical sequences of lithologies. Vertical profiles were established as environmental modelling tools by Visher (1965) and have been used to interpret the characteristics of fluvial systems by a number of authors including Miall (1977, 1978), Rust (1978b), Hayes and Kana (1980), and Levey (1980) (see Table 2.4.). However, both Miall (1980, 1985, 1988) and Walker (1990) agree that vertical profiles are not diagnostic features of sedimentary processes because similar cyclic sequences can be produced by different autocyclic and allocyclic processes and in different environmental settings. The limitations of vertical sequences as tools for interpretation of fluvial system planform (two dimensional fluvial morphology as observed in plan view) were demonstrated by Brierley (1989). Brierley observed vertical sequences in braided, wandering (slightly sinuous) and meandering reaches of the Squamish River, British Columbia. He used Markov chain analysis to show that no vertical sequence occurs exclusively in any one of the three planforms and that no vertical sequence was even characteristic of any particular planform. Miall, Walker and Brierley are therefore unanimous in suggesting that vertical analysis of sedimentary features cannot be used in isolation for diagnosis of fluvial system character. Friend (1983) qualifies this, stating that some very specific vertical sequences may be diagnostic and that thickness of units may be indicative of mode of accumulation. However, Friend uses features only of ephemeral channels as examples and does not detail sequences which might be used to interpret any other commonly described planform types.

2.4.1.2 Limitations of Opencast Mine Face Data

Outcrop scale data is available in the two opencast mines described in section 2.3.1. In opencasts, the lateral rate of variation of individual sedimentary beds is rapid for clastic sediments, which are continuous for only tens of metres, whereas coal seams are continuous for hundreds of metres. However as there is only one coal seam exposed in Opencast No. 6, coal seams are not useful for detailed correlation between the opencasts. It is not possible to correlate specific clastic horizons between the two opencast sections therefore analysis of lateral variability in sedimentary features is restricted to comparisons within each opencast. The principal limitation on outcrop data is that the two opencasts occupy a very small part of the coalfield and contain very limited intervals of the Morley and Beaumont Coal Measures sequences. Interpretations made for either of these opencasts cannot necessarily be applied to any other part of the coalfield, or other intervals in the coal measures sequences, because it is possible for fluvial systems to vary rapidly in space and time (e.g., Brierley (1989) and Smith et al. (1989)).

2.4.1.3 Limitations of Basin-Scale Correlations of Drillholes

Basin-scale data is another source of information at Ohai Coalfield which can be compared with existing facies models. Ohai basin-scale data relies on correlation of drill cores and includes

a) The morphologies of lithological units, i.e., sandstone, carbonaceous mudstone and coal, see Tables 2.1, 2.2 and Figs. 2.7 to 2.18.
b) Basin-wide lateral and vertical textural variation ('C'- and 'S'-horizons) and the geometry of individual lithologic bodies e.g., sandstone sheet, sandstone ribbon.

Fluvial Models Subdivided on the Basis of Fluvial Planform

Sandstone unit morphologies have been used to interpret basin-scale fluvial styles since Allen (1965) developed his classical models. An example of a sandstone morphology thought to be characteristic of a particular fluvial system is given by Smith and Smith (1980). They suggest that thick, laterally confined channel sands are characteristic of sediments deposited in an anastomosing system and developed a three-dimensional model for such fluvial systems. If one is to compare data to existing models, it is necessary to evaluate the criteria on which these models are based. Fluvial models in which the geometry of large-scale lithologic units (sandstone, mudstone, coal) are used to interpret fluvial style are generally based on the subdivision of all fluvial systems into a few categories of fluvial planform (see Table 2.4). The fluvial planforms recognised by most authors are straight, meandering, braided and anastomosing (Rust, 1978a). Geological usage of these subdivisions implies that the sedimentary record includes features which are diagnostic of individual fluvial planforms, i.e., every planform must deposit sediments with some characteristics that are not duplicated in any other planform. Sedimentary characteristics which have been used for interpretation of basin-scale fluvial planform include i) grain size, ii) two-dimensional vertical profiles and iii) three dimensional features such as epsilon cross-stratification. The potential of each of the above sedimentary characteristics to act as a diagnostic feature in the recognition of original fluvial planform is considered in the following paragraphs in order to determine whether planform can be deduced from the sedimentary record and therefore whether existing facies models are useful to compare data against.

Schumm (1963, 1981) considered that grain size acts as the primary control on fluvial planform development by influencing the mode of sediment transport. He associated particular grain sizes with particular planforms (see Table 2.4). Therefore, according to Schumm, the original planform of a fluvial system can be known merely from an assessment of the maximum grain size present in deposits from that system. The flaw in this approach can be seen from studies of modern rivers, for example, the Brahmaputra (Bristow, 1987) in which the maximum sediment size remains sandy but the river planform varies along its length between braided, meandering and anastomosing reaches. In addition, meandering river systems may be dominantly sandy or contain significant amounts of gravel (Carson and Griffiths, 1987). Present understanding of modern fluvial systems makes it clear that control of fluvial system planform is related to a number of factors, rather than any single factor such as grain size (Bridge, 1985). Friend (1983) states that '...the overall proportion of fine-grained sediment in a sequence must not, by itself, be used as an index of channel pattern."

The use of vertical profiles as diagnostic sedimentary features has already been discussed with reference to individual drill core data and the conclusion reached is that vertical profiles are not useful tools for interpretation of fluvial style.

Three-dimensional sedimentary structures are a third feature often used to interpret original fluvial planform. One such feature applied widely in sedimentological literature is epsilon cross-stratification (ECS), as proposed by Allen (1963). The occurrence of ECS in sediments is frequently used as evidence that the original fluvial planform was meandering, whereas lack of ECS is said to imply that the fluvial system was <u>not</u> meandering. However, ECS has been described in both braided (Miall, 1978) and anastomosing systems (Smith and Smith, 1980; Smith, 1983) therefore the presence of ECS does not necessarily indicate that deposition of sediment occurred in a meandering planform. Moreover, meandering systems containing no fine sediment do not develop ECS (Hayes and Kana, 1980; Levey, 1980), therefore lack of ECS cannot be used to conclude that the original planform was non-meandering. Smith (1987) observed that ECS is rare in the sediments of modern meandering systems but is very common in ancient sediments which are interpreted as meandering. Smith studied several modern meandering systems and found ECS only in the tidally-influenced reaches of these rivers. This may suggest that the association of ECS with meandering systems is, in fact, erroneous and that ECS may be indicative of a tidally influenced fluvial system but is characteristic of no particular fluvial planform. From this example it appears that three-dimensional sedimentary features may not be rigorous interpretive tools even where, for over two decades, such features have been considered to be diagnostic of a particular planform.

From the preceding discussion it would seem that neither grain size, vertical profiles nor three-dimensional sedimentary features provide a completely valid basis for the interpretation of original fluvial planform. Miall states that this problem occurs because a spectrum of channel morphologies have been illustrated in modern literature, "...that reveal a complete gradation between all four end members" (the straight, braided, meandering and anastomosing planforms of Rust (1978a)). This diversity of planforms exists because fluvial sedimentation is governed by a variety of partially interdependent controls (Bridge, 1985; Miall, 1985). No particular style of sedimentary deposition is unique to a particular channel morphology, therefore no characteristic observed in sediment can be diagnostic of any particular fluvial planform. Therefore fluvial models based on fluvial planform are not useful as standards against which to compare most data, such as the data on sedimentary body types available at Ohai Coalfield. Nor is development of such fluvial models a valid method for interpretation of depositional setting.

Fluvial Models Subdivided on the Basis of Criteria Other Than Fluvial Planform

Although it has been shown that comparison of sedimentary data with fluvial models subdivided on the basis planform is not useful, basin scale data can be compared to fluvial models which are subdivided according to criteria other than planform. One such criterion is tectonic style. Fluvial models have been developed for specific tectonic settings by authors including Miall (1981), Leeder and Gawthorpe (1987) and Alexander and Leeder (1987). These models are summarised in Table 2.5. The applicability of tectonic models to Morley Coal Measure sediments is discussed in section 2.4.2.1. Models subdivided on the basis of tectonic style are useful because the factors in the models which influence sedimentary processes, such as tilting or lateral movement, can be considered in isolation, are completely independent of the fluvial system and therefore create distinctively different sedimentary sequences. In contrast, models of autocyclic controls on sedimentation attempt to assess the effects of numerous interdependent controls which cannot be considered in isolation and therefore create similar sedimentary sequences.

Other alternative methods for development of fluvial models have been recently suggested, for example 'architectural-element analysis' (AEA) proposed by Miall (1985). AEA is a method of description of data from which three-dimensional models of fluvial systems can be constructed but in which there are no pre-existing subdivisions of fluvial styles. Sedimentary outcrops are described in terms of 8 sedimentary units which Miall considers to be the basic units comprising all fluvial systems e.g,. channel form, overbank deposit, and the relationships of these units are detailed. The limitation of Miall's method is that it requires widespread two dimensional, and preferably three dimensional, exposure of an extent that is not available at Ohai.

Another alternative use of basin-scale data is detailed by Friend (1983) who suggests that, although precise interpretation of original fluvial planform is not possible, certain elements of planform style can be interpreted from basin-scale sedimentary variation. For example, the geometries of sandstone and mudstone units can indicate the presence of channel forms or non-channelised flow, and degree of channel mobility i.e., fixed between episodes of abrupt switching, or mobile. Interpretation of sedimentary unit morphology in the style of Friend <u>is</u> applicable to the data available in Ohai Coalfield. Development of a precise fluvial model is not expected but broad characteristics of the clastic depositional environment are described.

In summary, fluvial planform cannot presently be interpreted from sedimentary grain size, vertical profiles or three-dimensional sedimentary structures, therefore models based on fluvial planform are not useful for comparison with data from Ohai Coalfield. In addition, outcrop data at Ohai is too restricted to be used for environmental modelling of the whole coalfield. Although it is not possible to place Morley and Beaumont sediments within a conventional fluvial facies models, certain features of channel behaviour and fluvial response to tectonic setting can be interpreted from basin-scale sedimentary data, and are described in the following section.

2.4.2 Depositional Relationships Between Clastic Sediment, Coal and Sub-basin Shapes

In this section the interpretations which can be made for Morley and Beaumont sedimentary environments are discussed separately for the two coal measure sequences. From the characteristics of the sedimentary environments, the relationships in both formations between accumulating peat and clastic sedimentation are inferred.

2.4.2.1. Characteristics of the Depositional Environments in the Morley Coal Measures

In the Morley Coal Measures, two major depositional environments can be identified:
1) 'S'-environments in which the 'S'-horizon sediment accumulated.
2) 'C'-environments in which the 'C'-horizon sediment was deposited.
'S'-horizon sediment accumulated in environments where fluvial activity and clastic deposition were generally dominant whereas there was comparatively little clastic input to the coalfield during the deposition of 'C'-horizons and mires were widespread. The lack of interfingering of 'S'- and 'C'-horizons suggests that the respective environments were generally not contemporaneous. The characteristics of deposition in these two environments are discussed separately.

'S'-environments

In the Morley Coal Measures, the characteristics of the 'S'-environments in the Ohai and Mossbank Basins differ. In the Ohai Basin, sediments deposited in the 'S'-environment were typically sand and mud, but occasionally carbonaceous mud and peat. Fluvial channels probably occupied only part of the sub-basin and were laterally associated with fine-grained floodplain sediments which were often vegetated (rooting of fine sediment is observed in the opencasts). In Figure 2.27 although sandstone is widespread throughout the sub-basin, there are areas of mudstone and carbonaceous mudstone, particularly towards the sub-basin margins. In contrast in the Mossbank Basin 'S'-environments, periods of widespread sand deposition alternated with periods of widespread carbonaceous mudstone deposition. However, the term 'S'-environment is used because clastic deposition was dominant and little peat deposition occurred.

Different sandstone body geometries in the 'S'-horizons (described in Tables 2.1 and 2.3) are interpreted as the products of different depositional mechanisms which were controlled by sub-basin structure. In the Ohai Basin, 'large' sandstone sheets generally occur towards the part of the sub-basin in which the least subsidence occurred (in the northeast) and are also more common in Ohai S4, the uppermost 'S'-horizon. Sandstone ribbons are more common in the parts of the sub-basin with the greatest total subsidence, in the southwest and along the sub-basin axis. The change in fluvial style, from a system depositing sheet sands to system in which vertical stacking of sand bodies (forming ribbons) occurred within a stable channel system, is attributed to varying rates of subsidence throughout the coalfield. The breadth of sandstone sheets in comparison with their thickness implies a lack of bank stability (Smith and Smith, 1980), and suggests that channels were not laterally confined. This contrasts with the sandstone ribbons, where channel morphology and location appear to have remained stable over considerable periods of time during which sandstone units were stacked vertically within floodplain sediments.

Channel stability is a characteristic of fluvial systems described by Smith and Smith (1980) in which the channels are stabilised by rapid aggradation resulting from rapid subsidence. Another mechanism which can create channel stability is rooting of channel margins (Smith, 1976) or a rise in base level created by impeded drainage (Smith and Smith, 1980). Any of the above mechanisms could have resulted in stable channels in the Ohai Basin. Rapid subsidence would be consistent with known fault-control of this sub-basin, which was actively subsiding during deposition of the Morley Coal Measures. A rise in base level could have been caused by restricted drainage to the south. Another mechanism which can result in stable fluvial channels is channel entrainment along an area of maximum subsidence created by fault movement which accords with the location of sandstone ribbons along the axis of maximum total subsidence in the Ohai Basin. Newman and Newman (in press) propose that entrainment of channels as the result of subsidence was the mechanism by which channels were stabilised in Greymouth Coalfield. The narrowing of the Ohai Basin demonstrated by variation in total sediment thicknesses (Fig. 2.19) may have influenced drainage patterns by confining channels to the constricted area of maximum subsidence.

The third sandstone unit morphology, composite sandstone sheets, is considered to imply greater continuity of sand supply. Composite sand sheets are particularly common in the north of the Ohai Basin (Fig. 2.10) where they may indicate more continuous sand deposition on the basin margin or, alternatively, that the lack of subsidence on the basin margin resulted in channels eroding any fine sediment deposited. The location of a composite sheet adjacent to the northern part of the Bluebottle High (Fig. 2.11), suggests that during deposition of the Morley Formation the Bluebottle High may have been actively eroded at times, supplying sediment to the surrounding area.

The sandstone units in the Mossbank Basin are thin and generally widespread, indicating that they were deposited by short-lived, high energy fluvial events which extended over much of the Mossbank Basin. Sheet-flooding is one mechanism which can create thin, extensive sand units (Abdullatif, 1989). The sandstone bodies in the Mossbank Basin 'S'-horizons thin to the east and south, suggesting that sand may have been sourced from the west and north of the sub-basin. The extensive carbonaceous mudstone horizons (which are of similar thickness to the sandstone horizons) in the 'S'-horizons of the Mossbank Basin suggest that there were lengthy periods when little coarse-grained clastic material was available. The carbonaceous mudstone may represent periods of lacustrine deposition and/or deposition from low energy mud-bearing streams.

'C'-environments

Sediments deposited in 'C'-environments in both the Ohai and Mossbank Basins were mainly peat, carbonaceous mud and mud together with small quantities of sand. The sandstone units that do occur are thin and cannot be correlated between drillholes. In the Ohai Basin sediment may have been transported westwards from the Bluebottle High, towards the peat-forming areas and also from north of the sub-basin as thick coal seams in the Ohai 'C'-horizons grade into carbonaceous mudstone northwards and to the west. There is no clear indication of the direction of sediment transport into the Mossbank Basin 'C'-environments. In general, the lack of sandstone in the 'C-horizons' suggest that little clastic sediment was transported into either of the sub-basins and that low energy channels transported only fine-grained sediment. However, because of the difficulties involved in correlating sediments between the sub-basins, there is no certainty that periods of low clastic input were synchronised for both sub-basins.

In the 'C'-environments peat accumulation was generally widespread. Initial sedimentation, of the carbonaceous mudstone which underlies many coal seams, may have been in shallow lakes surrounded by vegetation or in mires which were very frequently flooded, and a similar environment occurred after the death of long-lived mires in the Mossbank Basin. Rooting of the carbonaceous mudstone which underlies coal seams indicates that mires developed gradually from *in situ* vegetation, rather than initial peat accumulation being composed of allochthonous material. As lakes filled and channel margins were stabilised by vegetation large and persistent mires developed which were separated by low-energy streams transporting and depositing mud, but little sand. The location of muddy channels remained relatively constant during deposition of individual 'C'-horizons but were in different locations in each 'C'-horizon. For example, in Figure 2.8 there is carbonaceous mudstone in drillhole 364 splitting a thick coal seam throughout most of horizon O/C3 and in drillhole 335 carbonaceous mudstone is adjacent to the thick coal seam in much of horizon O/C4.

The dominance of mires in 'C'-environments probably was directly related to the paucity of clastic sediment associated with low energy fluvial activity Evidence that the 'C'-horizons represent periods of little active clastic deposition include:

i) 'Large' coal sheets are continuous across a large part of the sub-basins in which they occur.
ii) 'Large' coal sheets rarely split around sandstone units although splitting around carbonaceous mudstone units occurs.
iii) The majority of coal seams in 'C'-horizons contain little mineral matter (see Chapter 3).
iv) The areal distribution of lithologies in a time slice through a 'C'-horizon (Fig. 2.28) shows large coal bodies separated by areas of mudstone/carbonaceous mudstone.

Three different situations could account for the lack of coarse-grained sediment deposited in the Ohai and Mossbank Basins during 'C'-horizon accumulation as compared to 'S'-horizon deposition:

1) Coarse-grained sediment was not produced or was not transported from the sediment source area.
2) Coarse clastic sediment was produced but was transported through Ohai Coalfield without being deposited.
3) Coarse-grained sediment was produced and transported but was prevented from entering either or both of the sub-basins in Ohai Coalfield.

These three possibilities are considered below.

1) A number of interrelated factors could have resulted in a lack of coarse-grained sediment being produced or transported: a) insufficient relief for production of coarse sediment, b) insufficient relief for coarse sediment to be transported down-slope, c) climate and/or vegetation preventing erosion in the sediment source area, d) sediment provenance resulting in production of only fine sediment. a), b) and c) are possible mechanisms but d) is thought unlikely, as clasts in all Cretaceous conglomerates (see Chapter 1) indicate the Permian Takitimu volcanics were an important source of sediment throughout deposition of Cretaceous sediments in the Ohai Coalfield. Because of the lack of other Cretaceous sedimentary deposits in the vicinity of Ohai Coalfield, it is not possible to establish the validity of factors a), b) or c).

2) It is unlikely that transport of coarse-grained clastic sediment through Ohai Coalfield occurred without any deposition of coarse-grained sandstone beds. Although little coarse clastic sediment occurs in 'C'-horizon sediments, coal seams are frequently split by carbonaceous mudstone indicating sluggish fluvial activity coeval with peat formation. If a contemporaneous fluvial system was depositing mud-size particles it seems unlikely that current energy was strong enough to carry sand-size particles without depositing any sand.

3) The Ohai and Mossbank Basins may have periodically been physically protected from coarse-grained clastic input. Shielding of sub-basins from coarse clastics could have occurred as the result of changes in relative relief within and around the coalfield. Newman (1985a) and Newman and Newman (in press) attribute isolation of the Cretaceous Pike River Coalfield basins to switching of the locus of fluvial deposition between basins. Movement of a fluvial system between basins can be initiated by reduction in gradient as a result of channel aggradation or tectonic activity. At Ohai Coalfield it seems unlikely that the locus of coarse fluvial deposition switched between the Ohai and Mossbank Basins because the Mossbank Basin contains little coarse-grained clastic sediment. However, switching may have occurred between the Ohai Basin and another locus of deposition that is not now preserved. It is possible that the Mossbank Basin was shielded from clastic input by the basement highs to the northeast (the Moretown High) and west (the Bluebottle High). Paleocurrent indicators described by Sykes (1985) in the north of the Ohai Basin suggest that coarse clastic sediments were transported from northeast to southwest, towards the Mossbank Basin and also towards the Bluebottle High. Without the presence of the Bluebottle High, it seems likely that coarse clastics would have been transported into the Mossbank Basin. Although there is no evidence of paleohighs which might have sheltered the Ohai Basin it must be remembered that the Ohai Coalfield was a relatively small sedimentary basin (approximately 50 km^2) and therefore it is likely that the influences on depositional setting were similar throughout the coalfield.

In summary, the most likely mechanism that could have periodically isolated the Mossbank Basin from coarse-grained clastic sedimentation was the presence of the Bluebottle and Moretown basement highs. During deposition of 'C'-horizon sediments in the Ohai Basin, coarse clastic sediments were rarely transported beyond the sub-basin margins but the mechanisms by which coarse sediment was excluded from the sub-basin cannot be reliably ascertained. It is interesting to note that the Taratu Formation at Kaitangata Coalfield, which developed contemporaneously with the Morley Formation at Ohai Coalfield, also exhibits alternation of coarse- and fine-grained sedimentary horizons which are attributed by Raymond (1985) to periodic tectonic activity or switching of fluvial channels.

As well as characterising the depositional environments of individual sedimentary horizons, a general model for paleodrainage can be developed by comparison of Morley sediments with the models of Leeder and Gawthorpe (1987) which are particularly valuable because few paleoflow indicators can be identified in Morley sediments. Leeder and Gawthorpe developed two general models (Fig. 2.31) for the direction of drainage and style of sedimentary accumulation in structural depressions such as Ohai Coalfield. The models are based on the two possible drainage directions in an actively subsiding half-graben:

a) interior drainage (Fig. 2.31 (a))
b) through the basin, along the main axis of subsidence (Fig. 2.31 (b))

At Ohai Coalfield the main axis of subsidence was probably adjacent to the Twinlaw Fault and its eastern extension, the Wairio Fault. The most appropriate drainage model is interior drainage. Although there is no drill core information for sediment in the vicinity of the Twinlaw Fault, there are four lines of evidence supporting a model of interior drainage:

i) In 'C'-horizons coal seams thicken towards the Twinlaw Fault and are very rarely split by sand in the south part of the sub-basins. It is likely that a through-flowing fluvial system in the southern part of the coalfield would have sourced flood events and/or migrated laterally, splitting coal seams in the southern part of the area for which data is available. It is unlikely, in a basin as small as Ohai Coalfield, that a major fluvial trunk would not influence coal seams a maximum of 2 km distant. However, it must be considered that gradient control of a fluvial system is seen in Eocene coal measures at Buller Coalfield where flooding occurred a maximum of 1 km from the fluvial channel (Newman, 1987b).

ii) The fine/coarse-grained sediment ratio decreases southwards (Fig. 2.21). For the same reasons as outlined above, if a major fluvial system, presumably carrying a large load of coarse-grained sediment, was present in the south of the basin fine/coarse-grained sediment ratios would be expected to <u>increase</u> southwards.

iii) In 'S'-horizons the geometry of sandstone bodies changes from mainly 'large' sandstone sheets in the northeast to mainly sandstone ribbons in the southwest. As already discussed in this section, this change in fluvial style may indicate a back-up of ground water adjacent to the Twinlaw Fault, rather than a through-flowing system. However, it is also possible that a fluvial system could induce high ground water tables in its vicinity.

iv) The displacement on the Twinlaw Fault is at a maximum in the west therefore differential subsidence would probably have encouraged drainage from east to west. However, the conglomerates in the Wairio Coal Measures and New Brighton Conglomerate contain numerous granitic clasts which are interpreted to have been derived from the Fiordland Metamorphic Complex, to the west (Bowman et al., 1987). In addition, the Morley and Beaumont sandstones contain granitic lithic grains. There is no potential source of granitic material east of Ohai Coalfield therefore material was probably transported into the coalfield from the west, precluding the likelihood of east to west flowing fluvial systems within the coalfield.

If interior drainage occurred, it is likely that a lake may have developed at the southern margin of the basin because water was constantly moving towards that part of the basin and there is no evidence of a through-flowing system which could have drained the area.

2.4.2.2 *Characteristics of the Depositional Environments in the Beaumont Coal Measures*

In the Beaumont Coal Measures, three different sedimentary environments can be distinguished:

1) 'S'-environments in which relatively high energy clastic deposition was widespread
2) 'C'-environments in which only low-energy clastic deposition occurred
3) A 'C-S' environment, in the Ohai Basin, in which high energy clastic deposition appears to have been contemporaneous with relatively widespread deposition of fine-grained sediment.

The characteristics of these environments are discussed in the following paragraphs.

Sediments deposited in the 'S'-environments were sand, mud and small quantities of carbonaceous mud. Mossbank Basin 'S'-horizons are sandier than those in the Ohai Basin (Fig. 2.29), suggesting either that channels were more extensive or unstable in the Mossbank Basin and/or that fine-grained sediment was more commonly eroded. The large sandstone 'sheets' in the Mossbank Basin may have resulted from lateral movement of channels or from multiple channel development across the sub-basin. The eastward thinning and splitting into mudstone of the large sandstone 'sheet' in the O/S horizon suggests that there may have been an area of standing water in the eastern part of the Ohai Basin.

In 'C'-environments, peat and carbonaceous mud accumulated together with generally small amounts of sand (Fig. 2.30). Deposition of carbonaceous mud and mud probably occurred in shallow lakes because *Velesunio huttonii* , a freshwater bivalve, is very common in the fine sediments. Drainage was probably low energy and channels carried mainly muddy sediment. Occasionally higher energy channels deposited 'sheet' sands, however these sand units never extended across the whole of either sub-basin. Peat may have accumulated at lake margins because coal is associated with mudstone and carbonaceous mudstone. In addition, coal is most common towards the upper part of the carbonaceous mudstone units, suggesting that peat accumulation may have occurred when sediment infilled the shallow lakes. Coal seams are generally not shown in the cross-sections, being too thin and discontinuous to be visible at the scale drawn. Coal-rich units which formed in different 'C'-horizons occur in the same areas of the sub-basins, indicating that controls on peat accumulation or peat preservation were fixed relative to the sub-basin margins. Fault systems may have controlled peat preservation if subsidence lowered peat below sedimentary base level prior to erosive fluvial deposition. Fluvial erosion of Beaumont coal by an overlying sandstone units is visible in Opencast No. 6. Isopach patterns displaying rapid local decreases in the thickness of total coal (Fig. 2.24) indicate that either post-depositional of erosion of peat occurred or that fluvial activity contemporaneous with peat deposition limited the extent of mires.

In both sub-basins, although the lower and upper C-horizons contain sandstone beds these horizons do not interfinger with the large sandstone sheets in S-horizons. However,.the interfingering of M/C2 with M/S1 and M/S2 horizon sediments (Fig. 2.14) indicates that 'C'-environments and 'S'-environments were sometimes contemporaneous in the Mossbank Basin. In Figure 2.30, a time plane in the Mossbank Basin, it can be seen that carbonaceous mudstone was deposited in the north of this sub-basin (horizon M/C2) while sandstone was deposited in the south of the sub-basin (horizon M/S2). In the Ohai Basin contemporaneous deposition of coarse- and fine-grained sediments occurred simultaneously in the 'C-S' environment which is distinguished from 'S'-environments by the absence of large sandstone bodies. Also in Figure 2.30, a time plane through the 'C-S' horizon in the Ohai Basin, mudstone is widespread but local areas of carbonaceous mudstone, coal and sandstone appear indicating contemporaneous deposition of all these units. The 'C-S' environment may have been similar to the 'C'-environments except for the common, rather than occasional, presence of sand-bearing streams. A similar, "fluvio-deltaic" setting is described by Pocknall and Turnbull (1989) for Beaumont sediments in the Waiau Basin.

The relative scarcity of coarse-grained clastic sediment in 'C'-environments which were not contemporaneous with 'S'-environments may have resulted from shielding of the sub-basins by basement highs, similar to the setting suggested for the Cretaceous. Alternatively, sediment may not have been transported to the vicinity of Ohai Coalfield. The better development of 'C'-horizons in the Mossbank Basin than in the Ohai Basin suggests that the Mossbank Basin was, at times, better shielded from sediment input. However, when the 'C-' and 'S'-environments were contemporaneous within the Mossbank Basin and during deposition in the 'C-S'-environment in the Ohai Basin, controls on the grain-size of sediment deposited may have been related to either tectonic activity or to the style of sedimentary deposition.

2.4.2.3 Relationships Between Mires and Clastic Sedimentation, Morley Coal Measures

Two major depositional environments were associated with peat development in the Morley Coal Measures:

1) 'C'-environments in which mires were widespread and little high energy clastic deposition occurred.
2) 'S'-environments dominated by accumulation of clastics with restricted mire development.

Development of mires in 'C'-environments was probably directly related to the paucity of clastic sediment entering these environments and possibly lack of energy in the drainage channels. The mire flora lining the channels probably acted both to stabilise channel levées (Smith and Smith, 1980), if present, and also as a baffle impeding water and sediment movement into the mires. In addition, mires may have been domed and therefore raised above local flood events. Sedimentary data do not indicate whether peat bodies were domed, nor do petrographic characteristics of coal. However, it has been found that most modern mires are domed to some extent (Polack, 1950; Anderson, 1964; Sjors, 1983; Whitten et al., 1984) therefore doming of Morley peat cannot be discounted.

Mire death may have occurred when rates of sedimentation and fluvial activity increased and therefore peat accumulation ceased to keep pace with clastic sedimentation rates while channels became more erosive. This hypothesis is particularly likely in the Ohai Basin where sand often directly overlies coal seams. In the Mossbank Basin, widespread carbonaceous mudstone horizons overlie coal seams, suggesting that increasing energy and accumulation of coarse-grained clastics was not necessarily the cause of mire death. It is more likely that in this sub-basin rates of peat accumulation ceased to keep pace with tectonic subsidence and therefore flooding of mires occurred.

Morley mires also accumulated in 'S'-environments. Although these environments were dominated by coarse-grained clastic deposition and conditions were less suitable for mire development than in the 'C'-environments, there is evidence that some of the mires which did occur were isolated from clastic input. Although some coal seams in 'S'-horizons are mineral matter rich (>20% ash), hence were not effectively isolated from flooding, others contain relatively little mineral matter (<10% ash) and were therefore infrequently flooded. All coal seams in 'S'-horizons are small (Table 2.3) and only O/S4 contains many coal seams. Why O/S4 contains more coal seams than other 'S'-horizons is unclear; there does not appear to be any difference between the sandstone units found in O/S4 and other 'S'-horizons.

In Mossbank Basin 'S'-horizons, coal occurs laterally adjacent only to carbonaceous mudstone, therefore mires were probably isolated from clastic input by their occurrence in a low energy lacustrine or sluggish channel environment. However, in the Ohai Basin some coal seams occur in close proximity to sandstone bodies. Four possible mechanisms could explain the isolation of some peat in Ohai Basin 'S'-environments from clastic input.

1) Peat accumulated during short periods of little clastic input. Although some peat may have accumulated during periods of little clastic sedimentation, most coal seams shown in the composite cross-sections (Figs. 2.8, 2.9) appear to have formed contemporaneously with sand deposition. However the lack of lateral contacts between thin coal seams and sandstone units seen in the opencast faces provides evidence that some peat accumulation occurred during short breaks in clastic sedimentation, at least in horizon O/S4.

2) Peat was isolated from clastic sedimentation by characteristics of the fluvial system, such as confined channels, or because mires were sufficiently well removed from migrating fluvial channels not to be flooded.
3) Peat developed on abandoned channel sandstone bodies and was thus raised above most local sedimentation. Although some mires may have developed on abandoned channel sandstones e.g., a number of seams in O/S4 which overlie sandstone, other coal seams in 'S'-horizons overlie mudstone or carbonaceous mudstone.
4) The geometry of peat bodies was domed as suggested for peat in 'C'-environments and therefore peat was raised above any flooding. Whether peats were domed cannot be concluded from sedimentary or petrographic evidence but, as mentioned previously, the majority of modern mires are domed to some extent.

In summary, of the 'S'-horizons only O/S4 contains many coal seams and all of these are small. There are a number of mechanisms by which peat in O/S4 could have been isolated from clastic input and any one or more than one of these mechanisms may have been operative.

2.4.2.4 Relationships Between Mires and Clastic Sedimentation, Beaumont Coal Measures

In contrast to the thick, 'large' coal sheets which occur in the Morley Coal Measures, only thin, 'small' coal sheets occur in the Beaumont Coal Measures. The paucity of coal in the Beaumont Coal Measures indicates that depositional environments at Ohai Coalfield were generally unsuitable for peat accumulation during the Eocene. In particular, there are no coal seams in 'S'-horizons in contrast to the Morley Coal Measures in which coal seams occur in all horizons, including 'S'-horizons.

The 'C'-horizons, in which coal occurs in the Beaumont Coal Measures, were environments in which little coarse-grained clastic material was deposited. However, the amount of mineral matter in most Beaumont coal (over 25% ash, see Chapter 3), the small size of the coal seams and the evidence of erosion of peat in the opencast mines, indicate that, even in the 'C'-environments, peat was rarely completely isolated from clastic sedimentation. Mires were frequently flooded and probably short-lived as peat accumulation was frequently terminated by burial. The few mires which were not flooded (resulting in coal containing little mineral matter) may have developed remote from fluvial channels. In addition, these mires may have been more poorly drained therefore became acidic. When flooding occurred, the acidity of the environment resulted in clay flocculation towards the margins of the peat, therefore little mineral matter reached the centres of the mires (Staub and Cohen, 1979).

Some peat also accumulated in the 'C-S'-environment, in the Ohai Basin. This peat may have accumulated in lacustrine areas, removed from active clastic deposition (coal seams occur within carbonaceous mudstone bodies). As in the 'C'-environments, Beaumont mires in the 'C-S'-environment were probably frequently flooded and eroded.

In summary, peat accumulation was not favoured in Beaumont Coal Measure paleoenvironments. Most peat accumulation was short-lived and peat was frequently flooded. Peat accumulation mainly occurred in 'C'- environments in which little coarse-grained sediment was being deposited. Preservation of peat may have been dependent on local tectonic subsidence, which resulted in peat being below the level of erosion during subsequent fluvial activity.

2.5. SUMMARY

Review of the criteria for recognition of planform-based fluvial models suggests that they are not appropriate when data are of the type available for Ohai Coalfield. However, certain depositional characteristics can be interpreted for the Morley and Beaumont Coal Measures as well as the mechanisms which may have separated mires from clastic sedimentation. Conclusions about the sedimentary environments in which the coal measures were deposited include the following:

1) During deposition of the Morley Coal Measures, two major types of environment occurred, in both of which mires developed. These environments, which were non-contemporaneous, include:
   a) 'S'-environments: in which high energy fluvial systems deposited sand over much of the sub-basins and only small mires were present. The character of the fluvial systems varied laterally, probably mainly in response to tectonic controls on basin shape, and 'S'-environments in the Ohai and Mossbank Basins differed. In the Ohai Basin, unstable channels developed in areas of slower subsidence (depositing sandstone 'sheets') whereas stable channels developed in areas of more rapid subsidence (depositing sandstone ribbons). 'Composite' sandstone sheets in the north of the Ohai Basin suggest that either coarse-grained sediment was constantly transported into this part of the sub-basin or the slower subsidence resulted in erosion of any fine sediments deposited. In addition during early Morley deposition, coarse-grained sediment supply was sometimes more constant adjacent to the northern part of the Bluebottle High than in other parts of the Ohai Basin, resulting in the deposition of composite sandstone sheets. In addition, in the Mossbank Basin, 'thin' sheet sandstones were deposited during short-lived, widespread fluvial events during which sand was derived from the Bluebottle High and/or from the Ohai Basin. The widespread carbonaceous mudstone horizons in M/S1 and M/S2 indicate that there

were intervals of dominantly fine sedimentation, possibly in shallow lakes, between widespread, short-lived fluvial episodes.

Although mires were not common in 'S'-environments, the low mineral matter content of some coal seams in 'S'-horizons indicates that some mires were protected from sediment input. These mires may have been restricted to areas removed from clastic sedimentation, or raised above local sedimentation either by doming or because they developed on thick sandy channel deposits. Alternatively, mires may have developed during short-lived intervals of little clastic input; this is particularly likely in the Mossbank Basin.

b) 'C'-environments: in which, after initial sedimentation in shallow lakes and/or from widespread and unstable channels, extensive mires developed separated by low-energy streams depositing mainly mud and very little sand. The lack of clastic sediment present in 'C'-environments in the Mossbank Basin is attributed to the presence of basement highs shielding this sub-basin. The mechanism by which coarse-grained sediment was prevented from entering the Ohai Basin is not clear. Vegetational baffling and stabilisation of channels probably prevented flooding of mires. Mires may also have been domed and therefore raised above most local flood events. Recurrence of muddy deposition after peat accumulation in the Mossbank Basin may have resulted from rates of peat accumulation failing to keep pace with local tectonic subsidence, consequent flooding of mires occurring. Widespread mire death in the Ohai Basin may also have occurred when rates of sedimentation and fluvial energy increased (cessation of 'C'-environment conditions), leading to inundation of mires.

2) The general drainage pattern during Morley Coal Measure deposition, in both 'S'- and 'C'-environments, was probably interior drainage towards the Twinlaw and Wairio Faults. A lake may have developed adjacent to the Twinlaw Fault.

3) The style of deposition in the Beaumont Coal Measures can be separated into three main types:

   a) 'S'-environments: in which sand was deposited throughout much of the Ohai Coalfield although some mud was deposited in the Ohai Basin. Mud may have been deposited in the Mossbank Basin but later have been eroded. Migrating channels or widespread multiple channels deposited 'large sandstone sheets' throughout the coalfield. Sediment input was more continuous in the west of the Ohai Basin and the southwest of the Mossbank Basin, creating composite sandstone sheets.

b) 'C'-environments: in which mud and carbonaceous mud were deposited in an environment dominated by shallow lakes drained by low energy channels which transported mainly muddy sediment. Peat accumulated on lake margins and where lakes were infilled by sediment. Mires were frequently flooded and were rarely protected from clastic input. Preservation of peat may have depended on fault-controlled subsidence preventing erosion of peat.

Separation of 'C'- and 'S'-environments in space was probably related to both tectonic and sedimentary controls whereas separation of the two environments in time was probably due to the periodic tectonic elevation of basement highs preventing coarse-grained sediment from entering the sub-basins.

c) 'C-S'-environment: in which coarse- and fine-grained clastic sediment and peat were all deposited contemporaneously, possibly in a setting with sand-bearing streams feeding into shallow lakes and peat developing on lake margins. Peat was constantly flooded and often eroded and may have been preserved by fault-controlled subsidence, as in 'C'-environments.

CHAPTER 3

COAL CHEMISTRY OF SEAMS IN THE MORLEY AND BEAUMONT COAL MEASURES

3.1 INTRODUCTION

Chemical and mineralogical parameters may be used to assess coal quality and potential industrial usage as well as original mire character. Chemical analysis of coal provides information on moisture, ash, sulphur, volatile matter and energy content as well as on the major elements present in coal ash and the mineral assemblage in the coal. Knowledge of coal composition is important both for efficient utilisation of coal and environmental protection. Coal rank is evaluated on the basis of chemical parameters such as moisture and specific energy for low ranks and volatile matter for higher ranks. The degree of coal rank indicates both the burial history of coal and the suitability of coal for use in different industrial processes.

Peat chemistry and mineralogy are influenced by the prevailing environmental conditions during peat formation and can therefore be used to interpret the paleoenvironment in which peat developed. For example, Newman, J. (1985a, b, 1987c, 1989) used volatile matter to interpret changes in paleoenvironmental setting and climate. Where authigenic minerals do not contribute a large proportion of ash, the amount of ash in coal can be used to interpret the susceptibility of the paleomire to flooding. In this study the variations in coal chemistry, mineralogy and rank within the Morley and Beaumont Coal Measures are considered in order to evaluate changes in mire paleoenvironment from the Cretaceous to the Eocene. In addition, differences in chemistry between the Ohai and Mossbank Basins are identified and used to assess lateral variations within the coalfield. Comparison of the chemistry of coal seams from different formations and locations within Ohai Coalfield is of value because paleoenvironmental settings in this coalfield varied in both time and space (as discussed in Chapter 2).

3.2 METHODS

3.2.1 Sampling

Three types of samples were used for chemical analysis of coal seams from Ohai Coalfield:

1) Composite seam samples i.e. whole seam samples pre-crushed to less than 10 mm.
2) Ply samples pre-crushed to less than 10 mm.
3) Mine ply samples.

Many of the available composite samples had already been chemically analysed by the Coal Research Association (CRA). Ply samples were selected initially for petrography and then samples were chosen for chemical analysis on the basis of the petrographic analytical results. Mine samples for chemistry and petrography were collected together from two mine faces. In addition, sediment samples were collected from within 1 m of seam floors and roofs where drill core was available.

3.2.2 Analytical Methods

To assess whether chemical differences exist between seams of different ages and in different locations, 83 composite samples were chemically analysed. Sixty-nine samples from the Morley Coal Measures and 14 samples from the Beaumont Coal Measures were analysed (the ages and locations of samples are shown in Table 3.1). To determine the variability of chemical parameters within seams, 142 pre-crushed and mine ply samples were analysed, 134 from the Morley Coal Measures and 8 from the Beaumont Coal Measures (Table 3.2). Fewer composite and ply samples were selected from the Beaumont Coal Measures because of the lack of drillhole intersections in Beaumont seams and the high ash content of the coal. Proximate analyses were done on most composite and ply samples (see Tables 3.1 and 3.2 for a breakdown of the types of chemical analysis done on composite and ply samples). Sulphur determinations, analyses of specific energy and ultimate analyses were performed on some composite samples (Table 3.1). Determination of the major element oxides present in high temperature ash (HTA) was carried out for most composite samples and the majority of ply samples (Tables 3.1 and 3.2). X-ray diffraction (XRD) was performed on the low temperature ash (LTA) from a restricted number of ply samples (Table 3.2) which were chosen to represent the variations of major elements in ash. In addition, 10 sediment samples were analysed using XRD so that mineral matter in coal could be compared with mineral matter present in detrital sediment.

All proximate, specific energy, ultimate and sulphur analyses were performed by CRA according to the following standards:

1) moisture: ISO 5068-1983
2) ash: ISO 1171-1981
3) volatile matter: ISO 562-1981
4) total sulphur: ASTM 4239,
5) specific energy: ISO 1928-19766
6) carbon, hydrogen and nitrogen: Leco infrared inhouse method.

Major element oxide analyses of ash for composite samples were done by CRA using X-ray fluorescence (XRF) according to AS 1038 Part 14 (1981) but major element oxide analyses of ash for ply samples were done by XRF at the University of Canterbury. All XRD samples were analysed at the University of Canterbury by the author.

To provide ash for XRF, coal samples were initially pulverised to less than 30 µm in a ringmill. The resulting powder was then ashed in silica crucibles in an electric furnace, generally according to BS1016 Pt 3 (British Standards Institution, 1981). Samples were prepared according to the method of Norrish and Hutton (1969), later modified by Harvey et al. (1973) and Schroeder et al. (1980). Fusion beads were analysed on an automatic Philips PW1400 XRF from which the data was processed by on-line computer. Discs used for calibration were prepared from international standard rock powders.

For XRD analyses mineral matter was isolated from pulverised coal samples by a radio frequency plasma asher, LFE Corporation model LTA 304(2). Two or three samples were ashed simultaneously in each of the two chambers at settings optimised by Newman, N.A. (1988). Oxidation required between 8 and 24 hours to complete and all samples were stirred every 2 to 3 hours. The low temperature ashing process produces water-soluble artefacts as found by Rao and Gluskoter (1973). To remove artefacts produced by the ashing procedure a water-wash method was used which is described by Newman, N.A. (1988). In order to compare methods of sample preparation one LTA sample (39/237) was prepared both by washing and also as a mount ground in alcohol. All LTA samples were mounted as smears on glass slides and analysed in a Philips PW1820 diffractometer fitted with a copper tube and graphite monochrometer. Generator settings were maintained at 50 kV and 40 mA with scan rates of 1 degree per minute.

3.3 RESULTS

Results from chemical analyses of the Morley and Beaumont Coal Measures are divided into 1) data pertaining to mineral matter and other inorganic chemistry (proximate ash, XRD and XRF) and 2) data directly related to the organic component of coal (moisture, sulphur, volatile matter, specific energy and ultimate analyses). All results of chemical analyses are tabulated in Appendices C (composite samples) and D (ply samples).

The complex stratigraphy of the Morley and Beaumont Coal Measures makes definition of individual seam horizons problematic. As described in Chapter 2 seams do not extend basinwide and each drillhole may intersect from one to twenty coal seams. However the sedimentary horizons ('S'- and 'C'-horizons) in which seams occur are extensive (Figures 2.8 to 2.12 and 2.14 to 2.18). Because of the number of coal seams in the Ohai Coalfield, there are limited numbers of drillhole intersections in any one seam. Therefore, in order to achieve some comparison of composite chemical analyses, seams in the same horizon are considered together. Morley samples in the Ohai Basin are referred to according to the horizon they occur in, O/S4, O/C4, O/C3, O/C2 or O/C1 (O/C1 being the oldest). In the Mossbank Basin three coal-bearing horizons in the Morley Coal Measures were sampled for chemical analysis, M/S2, M/C2 and M/C1. Horizon C2 can be divided further into 4 sedimentary packages, each containing a thick coal seam (Fig. 2.11). Coal samples from these packages are referred to individually: M/C2a, M/C2b, M/C2c or M/C2d whereas all coal samples from horizon C1 are referred to as M/C1. A seam in M/C2c intersected in drillhole 375 contains two splits, M/C2c-i and M/C2c-ii.

No similarity between Beaumont seams in the same sedimentary horizons are apparent and few intersections occur in any one horizon therefore individual seam intersections from the Beaumont Coal Measures are not referred to except for the two intersections from which ply samples were taken. These intersections occur in the C1 horizons of the Ohai and Mossbank Basins and are therefore referred to as (Beaumont) O/C1 and M/C1.

3.3.1 Mineralogy and Inorganic Chemistry

"Mineral matter" as used in this thesis refers to all the inorganic components of coal, some of which may occur in non-mineral form. In contrast "ash" refers to the residue remaining after coal combustion. In this section the proportions of total ash, mineral data from XRD analyses of LTA and the major element oxides determined in HTA by XRF are described. Then, from comparison of the XRD and major element oxide data, formulae are derived for the calculation of mineral assemblages and total mineral matter in coal.

3.3.1.1 Total Ash in Coal Seams

Total ash was determined for all composite and ply samples (Appendices C and D) and values corrected to a dry basis (db). The Morley and Beaumont Coal Measures can generally be distinguished on the basis of ash values (as shown in Table 3.3). Coal from the Morley Coal Measures produces relatively little ash (seam horizon averages are 3 to 15% dry basis), as compared to seams in the Beaumont Coal Measures which average 16 to 40% ash. Within the Morley Coal Measures, coal seams from the Ohai Basin tend to produce less ash (mean of whole seams of 5.4% ash) and contain fewer partings of dirty coal (ash > 20%) or carbonaceous mudstone (ash > 50%) than do seams from the Mossbank Basin (mean of whole seams of 15% ash). Because only one composite sample from the Beaumont Coal Measures in the Ohai Basin was available for analysis, there is insufficient data to compare Eocene coal seams between the Ohai and Mossbank Basins. However, from the available data, it is evident that Beaumont seams in the Mossbank Basin are generally high ash (averaging 45%) whereas the Beaumont seam in the Ohai Basin contains only 5% ash.

The majority of ply samples from the Morley Coal Measures have ash values (db) of less than 8%. Plies with 8 to 20% ash are rare and most high ash plies yield more than 20% ash. The seams from horizons M/C2c-ii, M/C2b and M/C2a in drillhole 375, the seam from horizon O/C4 in drillhole 357 and location 1 in Wairaki No. 6 mine contain dirty coal/carbonaceous mudstone splits ranging in thickness from 5 cm to 1 m. The two Beaumont seams examined have very different ash values, the seam in drillhole 346 (Ohai Basin) averages 6% ash whereas the seam in drillhole 375 (Mossbank Basin) averages 42% ash (Table 3.4). The percentage of ash in coal seams generally increases towards seam roofs and floors (as shown in Figs. 4.7 to 4.10) as well as towards partings as has also been observed by Sykes (1985).

3.3.1.2 Mineral Matter in Coal and Sediment Samples

XRD was performed on 16 LTA samples, 13 from the Morley Coal Measures and 3 from the Beaumont Coal Measures (Table 3.4). Typical diffractograms for the coals and from the Morley and Beaumont Coal Measures appear in Appendix E. For comparison with coal LTA samples, 10 sediment samples from immediately below and above seams were analysed using XRD (Table 3.5).

The most common minerals found in coal samples from both the Morley and Beaumont Coal Measures are quartz, kaolinite, and three carbonate minerals (dolomite, calcite and siderite); less common minerals include illite, rutile and pyrite. Whewellite, a calcium oxylate, was present in some samples and is thought to be an artefact of the low-temperature ashing procedure. The minerals found in Morley coal samples are the same as the minerals documented by Sykes (1985) and Newman (1990) for Morley coal with the exceptions of aragonite and marcasite. Although Sykes identified these minerals in spot samples, they were not identified in this study.

Quartz was identified in all coal LTA samples. In polished coal surfaces quartz is visible as fine sand- to silt-size grains (Fig. 3.1 (a)) and compactional deformation of macerals around grains is common. Quartz grains may occur isolated within desmocollinite or may be abundant in layers associated with clay, liptodetrinite and inertodetrinite (Fig. 3.1 (b)). Clay is seen in polished surfaces both filling cell cavities in telinite (Fig. 3.1 (c)) and in layers associated with quartz grains, liptodetrinite and inertodetrinite (Fig. 3.1 (a)). The bulk of clay observed in the polished surfaces is probably kaolinite because all coal samples analysed by XRD contained kaolinite and only one sample (a very high ash Beaumont coal, 42/097) contained illite. XRD analysis of Beaumont LTA samples showed kaolinite to be poorly crystalline, whereas kaolinite in most Morley LTA samples is highly crystalline. From comparison of the relative heights of XRD peaks it can be seen that kaolinite and quartz are the two most abundant minerals in the majority of coal samples and that there are generally greater quantities of kaolinite than quartz in coal LTA (Table 3.4). Minor quantities of rutile are present in some samples although rutile was not observed in polished surfaces.

Dolomite, calcite and siderite were noted in most LTA samples and occasionally are the dominant mineral (Table 3.4). One sample (39/237) was prepared in both water and alcohol. The resultant diffractograms exhibited a dolomite peak for each preparation method but had a strong calcite peak in only the alcohol mount. This suggests that calcite may be under-represented in XRD diffractograms owing to loss during washing of LTA. When water was added to the ash, an acidic solution probably resulted in which the carbonate dissolved. Similar dissolution of calcite in XRD mounts was found by Rao et al. (1973). Carbonates are visible in polished surfaces, infilling cracks in telinite, telocollinite (Fig. 3.1.(d)) and semifusinite. At megascopic scale, carbonates occur as white veinlets in mine faces and carbonate-rich horizons may extend several metres horizontally.

Pyrite was identified in only one XRD sample (42/326) although isolated fine pyrite crystals up to 10μm in diameter are observed in polished surfaces. The percentage of pyrite in the mineral matter is evidently below the detection limits of XRD, which are estimated to be 2 to 5% (Stephen Brown, University of Canterbury, pers. comm.). The proportions of pyrite in LTA samples may also have been decreased by oxidation of pyrite after grinding and during ashing (Miller et al., 1979). The pyrite crystals are present within vitrinite and comprise a very minor proportion of total mineral matter counts.

The minerals identified by XRD in the ten sediment samples are documented in Table 3.5. All sediments from both the Morley and Beaumont Coal Measures contain kaolinite and quartz and most contain rutile. Kaolinite is the dominant mineral in all but two samples (the Beaumont sample from immediately above the seam in drillhole 375 and the Morley sample from immediately below seam 3 in drillhole 346). In addition, some Morley and Beaumont sediment samples contain interlayered clays. The Morley sample from 1 m below seam 1 in drillhole 346 contains both illite and smectite; illite/smectite occurs in one Beaumont sample (from 80 cm below the seam in drillhole 375) and two other samples contain illite (from immediately above and 1 m above the seam in drillhole 375). Poorly-crystalline kaolinite occurs in all Beaumont sediment samples and Morley samples from drillhole 346. However kaolinite in Morley sediment samples from drillhole 375 is highly crystalline.

3.3.1.3. Major Element Oxides In HTA

X-ray fluorescence was used to determine the major element oxides comprising the HTA in 75 composite samples and 75 ply samples (see Tables 3.1 and 3.2). All samples were analysed for SiO_2, Al_2O_3, TiO_2, Fe_2O_3, Na_2O, MgO, CaO, MnO, K_2O, P_2O_5 and SO_3. In addition, some composite samples were analysed by XRF for SrO and BaO. All major element oxide data is tabulated in Appendices C and D. In the following paragraphs major element oxides are grouped according to whether they display positive, negative or little correlation with the reciprocal of ash (db). Major oxides are plotted against the reciprocal of ash rather than against ash percentage for two reasons. Firstly, plotting oxides against the reciprocal of ash results in straight line relationships rather than logarithmic relationships (Fig. 3.2 (a), (b)). Secondly, in a plot against the reciprocal of ash the low ash samples are spread out (Fig. 3.2 (c), (d)), whereas plots against ash percentage emphasise high ash samples which are the most variable and the least representative of the character of the coal. Chemical analyses for both Morley and Beaumont samples are discussed together and differences in trends between the Morley and Beaumont Coal Measures noted. No consistent differences in the proportions of major element oxides in HTA distinguished the Ohai and Mossbank Basins or particular seams within the basins.

As shown in Figures 3.3 and 3.4, SiO_2, Al_2O_3 and TiO_2 all display a negative correlation with the reciprocal of ash (db), although the correlation of Al_2O_3 with the reciprocal of ash is unclear for ply samples, particularly Beaumont samples. Major element oxides which exhibit a strong positive correlation with the reciprocal of ash (db) are Na_2O, MgO, Fe_2O_3 (for composite samples only), CaO, SrO and BaO (Figs. 3.2, 3.5, 3.6). MnO, K_2O and P_2O_5 all display little correlation with the reciprocal of ash in composite or ply samples (Figs. 3.7, 3.8, 3.9). Outlying points on all graphs are considered in the discussion section. In addition to the relationships already described, CaO displays a positive relationship with Fe_2O_3 and MgO in both composite and ply samples (Figs. 3.10 and 3.11).

3.3.1.4 Comparison of Mineralogy of LTA and Composition of HTA and Calculation of Mineral Matter from HTA Composition

When the mineralogy of LTA and major element oxide chemistry of HTA are considered in conjunction, it is possible to interpret the mineral or minerals in which each major element oxide occurs. Normative analytical techniques can be used to calculate the proportions of each mineral present in the total mineral matter. To do this, however, it must be assumed that XRF analyses represent 100% of the HTA constituents.

All SiO_2 and the most of the Al_2O_3 in mineral matter occur in quartz and kaolinite. Small amounts of Al_2O_3 may be present in illite in some samples. The only mineral source of TiO_2 identified was rutile. Fe_2O_3, MnO and some of the CaO are present in siderite. Some Fe_2O_3 may also be present in small quantities of pyrite which are observed in polished surfaces; however this mineral was identified in only one XRD sample (42/326). The presence of MnO is siderite is suggested by the high percentages of both Fe_2O_3 and MnO in 42/638 and 42/320-1 (Figs. 3.10 (c), 3.11 (c)), in which siderite was identified. MnO has been found to occur in siderite in West Coast coals by Newman, N.A. (1988).

CaO and MgO are present in dolomite and CaO is also present in calcite. SrO and BaO may also occur in calcite and dolomite. Miller and Given (1978) and Newman (1990) both found that SrO and BaO substitute for calcium in calcite or magnesium in dolomite. Although Lindahl and Finkelman (1986) and Newman (1990), have found SrO and BaO occurring in phosphates, there is no relationship seen in Morley or Beaumont data when SrO or BaO are plotted against P_2O_5. As both SrO and BaO display strong correlations with the reciprocal of ash, a further possibility is that SrO and BaO are organically associated within the coal.

K_2O may occur in illite in a restricted number of samples. However, with the exception of traces of illite, which may host alkali metals, no mineral was identified in which Na_2O, K_2O or P_2O_5 occur. These three oxides may be present in minerals which occur below the limit of XRD detection or may be organically bound. Organic association of Na_2O is suggested by the strong positive correlation of this oxide with the reciprocal of ash (Fig. 3.2 (c), (d)) and the lack of any mineral containing sodium suggests this oxide is organically bound. K_2O and P_2O_5 do not display any good correlation with the reciprocal of ash (Figs. 3.8, 3.9) therefore are not wholly organically associated. However as each of these two oxides constitutes less than 1% of most HTA samples they do not have a significant affect on mineral matter calculations.

For satisfactory normative analysis of mineral matter to be made, it must be assumed that CaO, MgO and Fe_2O_3 occur in minerals and are not organically bound. It is generally accepted that noncrystalline components are rare in bituminous coals (Ward, 1989), although common in low rank coals (Kiss and King, 1977; Miller and Given, 1978) Sub-bituminous coals are not generally addressed by authors although Renton (1982) found that minerals in sub-bituminous coals and bituminous coals are similar. The mineral constituents in Morley and Beaumont coal are very similar to the minerals found in sub-bituminous and bituminous coals by Renton and in bituminous Australian and American coals by Ward (1986, 1989). Therefore, the assumption that noncrystalline components are not common in the Morley and Beaumont coal is justified on the grounds that the mineral matter assemblage contained in Morley and Beaumont coal is similar to the assemblages in other coals in which non-crystalline components do not form a significant proportion of the coal.

In addition to the theoretical justification given above, XRD results support the occurrence of CaO, MgO and Fe_2O_3 in mineral form. Carbonate minerals were identified in nine of fourteen Morley coal samples (Table 3.4). Some XRD samples were chosen for analysis because they contained high proportions of CaO, MgO or Fe_2O_3 and all these samples were found to contain carbonate minerals. It cannot be ruled out that some CaO, MgO or Fe_2O_3 may be organically bound but it is likely that most of these oxides occur in carbonate minerals.

Using the results outlined above, a series of assumptions as to the nature of mineral matter in Morley and Beaumont coal can be made for coals unaffected by marine influence (this generally follows the method described by Newman, N.A. (1988) for coals from the West Coast of the South Island):

1) No illite is present therefore all Al_2O_3 occurs in kaolinite. Where Al_2O_3 exceeds the amount of SiO_2 required to form kaolinite then excess Al_2O_3 is treated as a simple oxide.
2) SiO_2 not in kaolinite occurs in quartz.
3) All MgO occurs in dolomite. In a very few samples excess MgO remains and is then treated as a simple oxide.
4) All CaO not in dolomite occurs in calcite.
5) All Fe_2O_3 occurs in siderite.
6) MnO occurs in siderite, therefore can be treated as $MnCO_3$ and should be added to siderite.
7) All TiO_2 occurs in rutile.
8) Na_2O, K_2O and P_2O_5 are treated as simple oxides.

From assumptions 1) to 8) a series of equations can be produced to calculate the proportions of each mineral present in coal from the major element oxide chemistry of the ash as follows. These equations are based on normative analytical methods. Square brackets denote expression as an absolute percentage in whole coal on a dry basis.

1) $[\text{Kaolinite}] = [Al_2O_3] \times 2.53$
   Except where $Al_2O_3 > SiO_2 \times 1.176$ then $[\text{Kaolinite}] = [SiO_2] \times 2.15$
   and $[Al_2O_3] - [SiO_2] \times 0.85$ is treated as a simple oxide in step 8
2) $[\text{Quartz}] = [SiO_2] - [Al_2O_3] \times 1.176$
   Except where $Al_2O_3 > SiO_2 \times 1.176$ then $[\text{Quartz}] = 0$
3) $[\text{Dolomite}] = [MgO] \times 5.471$
   Except where $MgO \times 1.139 > CaO$ then $[\text{Dolomite}] = [CaO] \times 3.291$
   and $[MgO] - [CaO] \times 0.72$ is treated as a simple oxide in step 8
4) $[\text{Calcite}] = [CaO] - [MgO] \times 1.39$
   Except where $MgO \times 1.139 > CaO$ then $[\text{Calcite}] = 0$
5) $[\text{Siderite}] = [Fe_2O_3] \times 1.45 + [MnO] \times 1.2$
6) $[\text{Rutile}] = [TiO_2]$
7) $[\text{Simple Oxides}] = [Na_2O + K_2O + P_2O_5 + \text{excess } Al_2O_3 \text{ from step 1} + \text{excess MgO from step 3}]$

The proportions of minerals in coal were calculated for all composite and ply samples with XRF data. Results of the calculations are tabulated in Appendices C and D. When calculated mineral values are plotted against ash percentage, kaolinite, quartz and rutile all display strong positive correlations for both composite and ply data (Figs. 3.12, 3.13) whereas calcite, dolomite and siderite do not display a correlation (Figs. 3.14, 3.15). Mineral plots are shown on a log-log scale to emphasise the values of low ash coal samples.

Calculated mineral proportions can be used to derive a value for the ratio of mineral matter to ash (Appendices C and D) as follows:

[Mineral Matter] = [kaolinite] + [quartz] + [dolomite] + [calcite] + [magnesite] + [siderite] + [simple oxides]

Mineral Matter/Ash = [Mineral Matter] / Ash (dry basis)

The ratio of mineral matter to ash can be used for recalculation of parameters to a dry, mineral matter free (dmmf) basis. Values for water and carbon dioxide in mineral matter are also necessary for recalculation of volatile matter to a dry, mineral matter free basis. Mineral water and carbon dioxide can be calculated according to the following equations:

[Mineral H_2O] = [kaolinite] x 0.14

[Mineral CO_2] = [dolomite] x 0.477 + [calcite] x 0.44 + [$MnCO_3$] x 0.17 + [$FeCO_3$] x 0.38

3.3.2 Moisture, Sulphur, Volatile Matter, Specific Energy and Ultimate Analyses

3.3.2.1 Moisture

For Ohai composite and ply samples, moisture values are reported on one of three different bases, as-analysed (aa), air-dried (ad) or bed moist (bm). Moisture values for composite samples from the Mossbank Basin were measured at the time of analysis without special treatment (aa), whereas composite samples from the Ohai Basin and all plies were analysed after being dried at 20 degrees Celsius in 70% relative humidity for 12 hours (ad). Moisture results on an as-analysed or air-dried basis are reported in Appendix C. Ply samples from the seam in drillhole 364 from horizon O/C3 and from some seams in the Mossbank Basin were placed in a sealed container after removal from the drill core and were analysed for bed moisture. Moisture values (bm) are tabulated in Appendix C.

Direct comparison of moisture data cannot be made because different methods of moisture measurement were used for the samples. However because both as-analysed and air-dried moisture values are similar, general observations can be made; the moisture values of seams in both the Ohai Basin (ad values) and the Mossbank Basin (aa values) are between 11 and 14%. Bed moisture, rather than air-dried or as-analysed moisture, is required for calculation of American Society for Testing Materials (ASTM) parameters indicative of coal rank. Although bed moisture was not measured for most samples, bed moisture values were calculated from moisture aa or ad. For the Ohai basin, composite moisture values were corrected to a bed moist basis using the average bed moisture to air-dried moisture ratio in the seam intersection in horizon O/C3, drillhole 364. Mossbank Basin composite moisture values were corrected using the average bed moisture to as-analysed moisture ratio measured in each seam. Bed moisture values are always slightly greater than as-analysed or air-dried moisture values, averaging 1.07 times moisture values (aa or ad) for low ash coals and 1.11 times moisture values (aa or ad) for high ash coals.

3.3.2.2 Sulphur

Total sulphur in coal was determined for 66 Morley and 14 Beaumont composite samples (Table 3.1). All sulphur values are presented in Appendix C. Total sulphur (db) in Morley coal ranges from 0.13% to 0.31%, averaging 0.23%. In Beaumont samples total sulphur ranges from 0.06% to 0.61%, averaging 0.34% (as shown in Table 3.5). Sulphur values display no relationship to ash values. Sulphur forms were analysed for 5 Morley composites and 1 Beaumont composite sample. Analysis of sulphur forms shows that sulphur is in either organic or pyritic form. The proportions of organic and pyritic sulphur are variable. Sulphate sulphur was not detected in any of the samples.

Total sulphur values are required for correction of volatile matter and specific energy values. Sulphur values were determined for composite Ohai samples but not for ply samples. However, because there is little variation in the sulphur values of composite samples, it was assumed that the sulphur content of ply samples does not vary significantly. Therefore, sulphur values for ply samples (Appendix D) were assumed to be the same as the sulphur values for the composite samples from the appropriate seams.

3.3.2.3 Volatile Matter

Volatile matter analyses were performed on all Beaumont composite samples, all but two Morley composite samples and the majority of ply samples (Tables 3.1, 3.2). Volatile matter (VM) values are reported corrected to a dry, ash-free basis (daf) and a dry, mineral matter, sulphur-free basis (dmmSf) for all composites and plies with ash values less than 20% (values tabulated in Appendices C and D). Correction of volatile matter for coal with more than 20% ash, except for ply samples with individual major oxide analyses, was not attempted because errors in analyses and mineral matter calculations would have been magnified too greatly. Correction to a mineral matter-free basis was performed using calculated mineral matter values (from formulae described in section 3.3.1.4). Volatile matter (dmmSf) can be calculated using the following equation:

$$\text{Volatile Matter (dmmSf)} = 100 \times \frac{(\text{VM (db)} - ([\text{Min. } H_2O] + [\text{Min. } CO_2] + \text{Sulphur (db)} / 2))}{100 - ([\text{Mineral Matter}] + \text{Sulphur (db)})}$$

The above method for correction of volatile matter follows the method of normative analysis used by Newman, N.A. (1988). Newman, N.A. (1985) tested this method of normative correction by plotting corrected volatile matter against reflectance for West Coast coals in which a strong relationship between volatile matter and reflectance had already been proven. Corrections to volatile matter using normative analysis were demonstrated to improve the correlation coefficient for the relationship between volatile matter and reflectance, as compared to VM (daf) and VM corrected by the method of Suggate (1959).

In this thesis correction of volatile matter to a dmmSf basis for ply samples without major oxide data required estimation of the mineral water and carbon dioxide and mineral matter to ash ratios. Water associated with mineral matter has a strong positive correlation with ash (db) as shown in Figure 3.16 (a) but neither carbon dioxide in mineral matter (Fig. 3.16 (b)) nor the mineral matter to ash ratio correlate with ash values. Therefore, for ply samples without major oxide data, mineral water was calculated from ash (db) but an average value of mineral carbon dioxide and the mineral matter to ash ratio were determined for each seam. Then volatile matter was calculated according to the equation below (unless stated otherwise all values are on a dry basis):

$$\underset{\text{(dmmSf)}}{\text{Volatile Matter}} = 100 \times \frac{(\text{VM} + 0.274 - (\text{Ash} \times 0.104 + \text{average } [\text{Min } CO_2] + \text{Sulphur}/2)}{100 - \text{Ash } \times \text{average Mineral Matter/Ash} - \text{Sulphur}}$$

Variations in VM (dmmSf) values for Morley and Beaumont coals are shown in Tables 3.5 (composite samples) and 3.6 (ply samples). Morley coal seams have lower VM (dmmSf) values (ranging from 39% to 47%) than Beaumont seams (49-56%). There is no significant difference between the VM (dmmSf) values for coal from the Ohai and Mossbank Basins. VM (dmmSf) values for ply samples have ranges similar to the values for composite samples. Variations in volatile matter within seams are considered in detail in chapter 4 in association with petrographical variations.

3.3.2.4 Specific Energy

Specific energy (SpE) was determined for 66 Morley composite samples and 14 Beaumont composite samples (Table 3.1). Specific energy values corrected to dry ash-free (daf), moist mineral matter sulphur-free (mmmSf) and dry mineral matter sulphur-free (dmmSf) bases are listed in Appendix C. As for volatile matter values, only samples containing less than 20% ash were corrected to a mineral matter-free basis.

Correction of specific energy to a mmmSf basis requires bed moisture values for coal samples. Bed moisture values were calculated for composite samples as described in 3.3.2.1. Calculation of SpE (mmmSf) was performed using two methods, the Parr formula and mineral matter to ash ratios calculated from major oxide data. Both correction formulae are shown below (all values are expressed on a bed moist basis unless otherwise stated) :

$$\text{Specific Energy (mmmSf Parr)} = 100 \text{ x } \frac{(\text{Specific Energy} - 0.116 \text{ x Sulphur})}{100 - (1.08 \text{ x Ash} + 0.55 \text{ x Sulphur}} \text{ Mj/kg}$$

$$\text{Specific Energy (mmmSf)} = 100 \text{ x } \frac{(\text{Specific Energy} - 0.095 \text{ x Sulphur})}{100 - (\text{Mineral Matter/Ash x Ash } + \text{Sulphur}} \text{ Mj/kg}$$

The SpE (mmmSf) values calculated from the two equations are very similar for any particular sample. In any one sample, the maximum difference between SpE (mmmSf) values calculated using the two formulae was 0.3 Mj/kg. Average Morley seam values of SpE (mmmSf) range from 23 Mj/kg to 24 Mj/kg for seam intersections in horizons O/S4, O/C4 and O/C3 in the Ohai Basin but seam intersections in horizon O/C2 average 25 Mj/kg. In comparison, SpE (mmmf) values are generally lower in the Mossbank Basin, from 21.5 Mj/kg to 22.0 Mj/kg for the averages of seam intersections in horizons M/S2, M/C2d, M/C2c-ii and M/C2b although intersections in horizons M/C2a and M/C1 have averages of 23.6 Mj/kg and 23.8 Mj/kg respectively (Table 3.3). SpE (mmmf) was calculated for only two Beaumont seam intersections; these have SpE (mmmSf) values of 18 Mj/kg and 25 Mj/kg (Table 3.3). The large difference between these values can be attributed to differences in measured bed moisture which may reflect rank variation.

Specific Energy was also corrected to a dry, mineral matter sulphur-free basis (Appendix C) using the following formula (all values on a dry basis unless otherwise stated):

$$\text{Specific Energy (dmmSf)} = \frac{100 \text{ x (Specific Energy} - 0.095 \text{ x Sulphur)}}{(100 - (\text{Mineral Matter/Ash x Ash} + \text{Sulphur})} \text{ Mj/kg}$$

Morley seam averages of SpE (dmmSf) range from 31 Mj/kg to 33 Mj/kg in the Ohai Basin and from 31 Mj/kg to 32 Mj/kg in the Mossbank Basin. The two Beaumont seam intersections for which SpE (dmmSf) was assessed have values similar to the Morley seams, 31 Mj/kg and 32 Mj/kg.

3.3.2.5 Ultimate Analytical Data

Ultimate analyses were performed on 71 composite samples, 58 from the Morley Coal Measures and 13 samples from the Beaumont Coal Measures. Results were corrected to a dry mineral matter sulphur-free basis (dmmSf) for all seams with ash values less than 20%. Carbon was also corrected for mineral carbon. The following formula was used to correct ultimate results for total carbon:

$$\text{Carbon (dmmf)} = \frac{100 \times \text{Carbon (ad or aa)} - ([\text{Mineral } CO_2] \times 0.2727)}{(100 - (\text{Moisture (ad or aa)} + \text{Ash (ad or aa)} \times \text{Mineral Matter/Ash})}$$

Total hydrogen, nitrogen and sulphur were corrected as follows:

$$\text{Ultimate Value (dmmf)} = \frac{100 \times \text{Ultimate Value (ad or aa)}}{(100 - (\text{Moisture (ad or aa)} + \text{Ash (ad or aa)} \times \text{Mineral Matter/Ash})}$$

Total oxygen (dmmf) was calculated as:

$$\text{Oxygen (dmmf)} = 100 - (\text{C (dmmf)} + \text{H (dmmf)} + \text{N (dmmf)} + \text{S (dmmf)})$$

Average seam values of ultimate results are shown in Table 3.5. Average values of carbon (dmmf) range from 77% to 79% for all Morley and Beaumont seam horizons. The average ratios of hydrogen to carbon range from 0.82 to 0.86 in all Morley seam intersections but in the two Beaumont seam intersections for which ultimate results (dmmf) were calculated, hydrogen/carbon (dmmf) is equal to 0.91 and 0.98. Oxygen to carbon ratios range from 0.15 to 0.16 in all seam intersections except for those in horizon O/C2 (Ohai Basin), in which oxygen/carbon (dmmf) equals 0.13.

3.4 DISCUSSION

3.4.1 Origin of Mineral Matter in Morley and Beaumont Coal

In this section the origin of mineral matter in coal from Ohai Coalfield is discussed and related to the paleo-peat depositional environment where possible. In addition the mineral matter in sediments is compared to the mineral content of the coal. There are a number of classification systems for mineral matter and these systems are often based on the inferred time and/or inferred process of formation of mineral matter. A useful classification scheme is that of Gluskoter et al. (1981) in which mineral matter is divided primarily into 1) detrital mineral matter, transported into the coal basin during peat accumulation, 2) authigenic mineral matter, inorganic species formed *in situ*. Authigenic mineral matter is further divided into a) syngenetic, formed during initial stages of coalification and b) epigenetic, formed after initial stages of coalification. The use of such a classification system clarifies which mineral matter components can be attributed to fluvial incursions into the mire (detrital), which components are related to the chemical characteristics of the peat environment (syngenetic) and which components are related to post-depositional controls (epigenetic). One problem with this system and other classification schemes is that it is not always possible to distinguish detrital minerals from syngenetic minerals, particularly where remobilisation of originally detrital minerals has occurred. Furthermore, because coalification is a continuous process, it is not necessarily appropriate to separate syngenetic minerals from epigenetic.

For the Morley and Beaumont coals in the Ohai Coalfield, the rutile, illite, most quartz and some kaolinite are interpreted to be detrital, some kaolinite and possibly some quartz are thought to be authigenic-syngenetic, and carbonate minerals and pyrite are interpreted as authigenic. In addition, no mineral was found in which the major element oxides Na_2O, K_2O and P_2O_5 occur, therefore these elements may be occurring as organically associated mineral matter.

3.4.1.1 Kaolinite, Quartz, Rutile and Illite - Dominantly Detrital Minerals

Evidence leading to an interpretation of kaolinite, quartz, rutile and illite as detrital includes

1) The negative relationship seen when Al_2O_3, SiO_2 and TiO_2 are plotted against the reciprocal of ash (Figs. 3.3, 3.4).
2) The presence of quartz and clay in mineral-rich layers on polished surfaces (Fig. 3.1 (a)).
3) That the minerals present in high ash coal adjacent to partings or seam margins are dominantly kaolinite and quartz.

However, in some cases kaolinite may also be of syngenetic origin. Cell void-filling clay (Fig. 3.1 (b)) is evidence of syngenetic crystallisation of clay. In addition, the crystallinity of kaolinite in most Morley coal samples indicates *in situ* leaching of detrital kaolinite and reprecipitation of kaolinite from solution (Ward, 1989), that is, syngenetic formation. In a leaching environment (Weaver, 1967; Millot, 1970) kaolinite may also be formed from other detrital clays. Conversely, the lack of crystallinity in Beaumont coal samples indicates little *in situ* leaching of kaolinite. The scatter in the correlation of Al_2O_3 in ply samples with the reciprocal of ash may indicate that some syngenetic kaolinite was formed from ions released by the humic material, as well as from detrital clay, resulting in organic association of the mineral. It is not possible to evaluate the truly non-detrital kaolinite component.

Syngenetic quartz has been reported in coal samples by Ruppert (1985) and Newman, N.A. (1988) but there is no evidence for or against syngenetic quartz crystallisation in Morley and Beaumont coal. However, Sykes (1991) found small quantities of late diagenetic quartz in Morley coal. This quartz occurs in distinctive 'hard bars' in the coal seams which result from late diagenetic replacement of carbonate minerals and coal.

3.4.1.2 Calcite, Dolomite, Siderite and Pyrite - Authigenic Minerals

Calcite, dolomite, siderite and pyrite are all interpreted to have an authigenic origin. Evidence supporting authigenic formation of carbonate minerals and pyrite includes the lack of association of carbonates or pyrite with mineral-rich layers in the coal and the occurrence of pyrite as micro-crystalline aggregates which Mackowsky (1968) considered to be syngenetic. In addition, the major element oxides contained in the carbonates and pyrite, CaO displays a strong positive correlation with the reciprocal of ash while MgO and Fe_2O_3 display weaker positive correlations (Figs. 3.5, 3.6). These relationships suggest that the carbonates are at least partially organically associated therefore must have developed syngenetically. Carbonate minerals frequently occur in fractures in coal macerals indicating that substantial coalification of peat had already occurred when the carbonate was deposited epigenetically.

Carbonate minerals fill fractures in telocollinite, telinite and semifusinite visible in both hand specimen and on polished surfaces. However, it is likely that a considerable proportion of carbonate minerals are extremely fine-grained and are not visible in polished surfaces under the magnification used (X 640). The presence of fine-grained carbonates is suggested by the lack of visible carbonates in samples containing over 25% CaO and in which mineral calcite was identified using XRD (32/235, 29/249 and 42/326 in Fig. 3.6 (b)). Furthermore, water-washing of XRD samples resulted in removal of calcite which would occur only if the calcite was very fine-grained. The presence of these very fine-grained carbonates is evidence for organic association of CaO, MgO and Fe_2O_3 in crystalline form.

Ward (1986, 1989) described formation of siderite during early diagenesis (syngenetic) and of calcite and dolomite during late stages of diagenesis (epigenetic). It is probable that carbonate minerals in Morley and Beaumont coal are both syngenetic and epigenetic. The fine-grained carbonates may have crystallised from ions released during peatification. Epigenetic remobilisation of the syngenetic carbonate resulted in carbonate filling cleats. Remobilisation is the most likely source of epigenetic carbonate because none of the strata directly overlying the Morley and Beaumont sequences contain carbonate rocks; hence there is little evidence for a source of carbonates which could have been introduced into the coal measures.

3.4.1.3 Elements in Organic Associations

The strong positive relationship of Na_2O with the reciprocal of ash (Fig. 3.2), indicates that sodium occurs in organic association within the coal. Organic association of sodium in the Paparoa coals of the West Coast is documented by Newman, N.A. (1988). As XRD analysis did not reveal any mineral species in which sodium occurs it is probable that sodium is organically bound.

In contrast to Na_2O, K_2O displays no correlation when plotted against the reciprocal of ash (Figs. 3.8, 3.9). In most coal samples no mineral was identified in which K_2O could occur except for one high ash Beaumont XRD sample which contained illite. It is possible that all the Beaumont ply and composite samples which display high K_2O in Figs. 3.8 (a) and (b) contain some proportion of illite. However XRD scans of Morley ply samples containing over 2% K_2O in ash (42/320-1, 42/317, 42/330, 42/322 in Fig. 3.8 (b)) revealed no illite peaks. Illite may have been present in amounts below the detection range of the XRD, alternatively K_2O may be organically bound; the mode of occurrence of K_2O in Morley Coal Measure samples remains uncertain. If K_2O is both organically bound and present in crystalline form then no correlation with the reciprocal of ash would be expected.

Like K_2O, P_2O_5 does not display a correlation when plotted against the reciprocal of ash. Apatite, a phosphate mineral, was identified in Morley coals by Sykes (1985). The proportion of P_2O_5 in Ohai coal analysed in this thesis is generally less than 0.5% therefore P_2O_5 may be present in apatite, or other phosphates, which occur in proportions below the level of XRD detection. Alternatively, P_2O_5 may be organically bound. As suggested for K_2O, if P_2O_5 is both organically bound and present in a crystalline form then the lack of correlation with the reciprocal of ash would be expected. Proportions of P_2O_5 of over 0.5% are present in the following ply samples shown in Fig. 3.9 (a): 39/233, 39/234, 39/237, 39/239, 39/247, 42/097, 42/313, 42/314, 42/315, 46/857, 46/858. Newman, N.A. (1988) proposed that phosphorus enrichment of peat can occur as the result of three mechanisms: 1) phosphate influx from surrounding soils, 2) concentration by oxidation of organic matter at the peat surface and 3) from intense or prolonged fixation of phosphate by reaction with Al and Ca species. All these three mechanisms may have been responsible for concentrating P_2O_5 in Morley and Beaumont coals. Plies 39/233 and 39/247 are both 2% to 3% higher in ash than surrounding plies; plies 39/237 and 39/239 are on either side of a carbonaceous mudstone parting in the coal seam and 42/097 is from a thin and dirty Beaumont seam. The association of phosphorus enrichment with locally increased ash content suggests phosphorus was derived from clastic mineral matter introduced by flooding (mechanism 1). In addition, the enrichment of phosphorus in plies which occur immediately adjacent to high phosphorus plies suggests mobilisation of phosphorus in the mires (mechanism 3). Plies 42/313 , 42/314 and 42/315 are all from a thin Beaumont seam and therefore may have been

0.3 – 0.5
42/098 + 099 - dirty Beaumont seam, 1 ply low P, low Fe
46/859 - above 857 + 858
46/852 - seam base also oxidised

42/132 seam base, high ash, raised Fe
0.1 – 0.2
42/320-1 below high ash, higher I
no data on high ash ply

enriched in phosphorus by fixation of mobile phosphorus derived from the overlying sediment (mechanisms 1 and 3). Plies 46/857 and 46/858 are distinctive in that they contain over 10% inertinite. The high proportion of inertinite in these plies suggests that they were subjected to increased oxidation and therefore phosphorus may have been concentrated by mechanism 2. The greater variability of P_2O_5 values in high ash Beaumont seams may reflect development of seams in more varied environmental settings as compared to high ash Morley seams.

857/858/859 below parting, high I, high Fe

3.4.1.4 Mineral Matter in Sediments

Mineral assemblages found in sediment samples from below and above coal seams add strength to the interpretations described above for the origin of mineral species in coal from Ohai Coalfield. Quartz, kaolinite and rutile, which were interpreted as mainly of detrital origin in coal, are present in all sediment samples and kaolinite is generally the dominant mineral. The presence of mixed layer smectites and illite in some sediment, but not in low ash coal, suggests that alteration of clays to kaolinite was ubiquitous in the mire environment. The lack of clays other than kaolinite in some sediment samples suggests that detrital sediments also may have undergone leaching during or following deposition. The highly crystalline nature of kaolinite in Morley sediment samples from drillhole 375 indicates intense leaching.

3.4.1.5 Summary

In summary, the mineral matter assemblage found in Ohai coal has varied origins. Rutile and illite are probably always of detrital origin as is the majority of the quartz in the coal except for the epigenetic quartz present in 'hard bands' Kaolinite may have a detrital or syngenetic origin; syngenetic kaolinite formed from remobilised detrital clay or from ions released during peatification. Carbonate minerals and pyrite are authigenic minerals. Pyrite was probably formed syngenetically, as it occurs in micro-crystalline aggregates while the carbonates probably developed both syngenetically and epigenetically. The epigenetic formation of carbonate minerals may have been from ions newly released by the organic matrix or from remobilisation of syngenetic carbonates. Na_2O is most likely to be organically bound. K_2O and P_2O_5 are probably both organically bound and exist in minerals present in only trace amounts in the coal. In some cases, K_2O occurs in illite, particularly in Beaumont samples. High values of P_2O_5 provide additional information on mire character, indicating that phosphate may have been brought into mires during flooding or that concentration of P_2O_5 resulted from increased oxidation in a peat layer.

3.4.2 Correlation of Ash and Calculated Kaolinite/Quartz Ratio

The ratio of calculated kaolinite to quartz in HTA varies in both composite or ply samples; in composite samples this ratio typically ranges from 1 to 10 and in ply samples it is generally in the range 1 to 5. In both composite and ply samples the ratio of kaolinite to quartz varies significantly in only very low ash samples.

Petrologic and XRD analysis of sandstones found their composition to be dominated by quartz (70-90% quartz as shown in Appendix F). In contrast, XRD analysis of mudstones showed that these sediments are kaolinite-rich (Table 3.5). If coarse-grained sediments are quartz-rich and fine-grained sediments are kaolinite-rich, it would seem likely that only fine sediment was introduced to the peat mire because most of the mineral matter in coal is kaolinite-rich (Table 3.4). The interpretation that detrital material in mires was derived from low-energy hydrodynamic activity accords with the conclusion from Chapter 2, that fluvial activity occurring during Morley Coal Measure peat accumulation was of low-energy and chiefly transported fine-grained sediment.

All samples in which the ratio kaolinite/quartz is less than 1 contain little mineral matter, therefore it is probable that the increased proportion of quartz in these samples is the result of syngenetic leaching of kaolinite or crystallisation of quartz. Samples with very high proportions of kaolinite are also all low ash. These samples probably contain syngenetic kaolinite, remobilised from elsewhere in the coal.

3.4.3 Rank Variation in the Morley and Beaumont Coal Measures

Coal rank refers to the degree of thermal maturity attained by a coal. It is necessary to assess variation in coal rank within Ohai Coalfield to determine whether changes in chemical parameters are affected by coal type. Ohai coals are of relatively low rank, therefore the most useful parameter for evaluating changes in rank is SpE (mmmf) calculated using the Parr formula (American Society for Testing and Materials, 1987b). Reflectance is not generally a useful rank parameter for sub-bituminous coals and is influenced by coal type in Ohai coals (as discussed in Chapter 4). Reflectance in Morley coals varies between 0.37 and 0.49. Morley composite samples and one Beaumont composite sample have SpE (mmmf) values ranging from 20.70 Mj/kg to 26.13 Mj/kg with seam averages ranging from 21 Mj/kg to 24 Mj/kg (Table 3.3). According to ASTM Standard D388-84 (1987b) all Ohai coals are of sub-bituminous rank, varying from sub-bituminous C through to A. A sub-bituminous rank for Ohai coals accords with the swelling indices of zero found for all Ohai coals (Appendix C.). The range in rank found for the samples in this thesis is smaller than that recorded by both Bowen (1964) and Bowman et al. (1987) who used specific energy values to class Ohai coal as sub-bituminous C to high volatile-bituminous A. The discrepancy between the ranges or perhaps even the breadth of the ranges may relate to the difficulty of collecting and satisfactorily analysing bed moist samples. Incorrect bed moisture values can significantly affect rank assessments based on SpE (mmmf).

Coal rank appears to increase significantly with increasing depth because stratigraphically lower seams have higher average values of SpE (mmmf or dmmf, Table 3.3). In the Ohai Basin, Morley seams intersections in horizons O/S4, O/C4 and O/C3 have seam averages of 23 Mj/kg to 24 Mj/kg (mmmf) whereas seam intersections in horizon O/C2 average 25 Mj/kg. SpE value of 25 Mj/kg. In the Mossbank Basin seam intersections in horizons M/S2, M/C2d, M/C2c-ii and M/C2b all have seam averages of 21.5 Mj/kg to 22 Mj/kg (mmmf) but seams in horizons M/C2a and M/C1 average 23.6 and 23.8 Mj/kg (mmmf) respectively. In addition, where SpE values are available for more than one seam in a single hole, the value of SpE (mmmf) generally increases down-hole (Fig. 3.18), indicating down-hole increases in rank. Down-hole increases in rank are more marked in the Ohai than in the Mossbank basin. The very low SpE (mmmf) of Morley sample 42/630 in drillhole 379 may indicate that this seam is of lower rank because burial depths decreased towards the far southeastern margin of the coalfield, where no Morley Coal Measure sediment is preserved. Total carbon values are an alternative rank indicator (Stach et al., 1982) and support conclusions of vertical variations in rank because total carbon (dmmf) increases in lower seams in both the Ohai and Mossbank Basins (Table 3.3). It is uncertain whether Beaumont coal seams differ in rank significantly from Morley seams because there are too few low ash Beaumont seams for comparison of mineral matter free parameters to be made.

Lateral rank variations within seams cannot be assessed because too few data points exist for contouring SpE values within any individual seam. In addition, comparison of rank variations within the coalfield is hindered by the fact that coal seams cannot be correlated between the Ohai and Mossbank Basins. However, a general comparison of rank in the two basins can be made using a "Suggate-rank" plot. Suggate (1959) proposed the "Suggate-rank" method for comparing variations in both coal rank and type on a single two-dimensional plot of SpE (dmmSf) versus VM(dmmSf). Suggate plots have been used for New Zealand coals by Newman (1989) and Newman and Newman (in press).

In Figure 3.19 (a) Morley composite samples are displayed on a Suggate plot. Morley coals can be seen to vary in type (scatter parallel to the lines of Suggate Rank) as well as varying in rank (scatter perpendicular to the lines of Suggate Rank). Coals from the Ohai Basin generally plot at a higher rank than do coals from the Mossbank Basin (Fig. 3.19 (b)). No within-basin trends can be discerned for the Ohai Basin but in the Mossbank Basin samples from drillhole 375 (in the southwest of the sub-basin) appear to be of higher rank than most other Mossbank Basin coals (Fig. 3.19 (b)). Therefore it appears that rank in the

Ohai Coalfield increases towards the west of the Mossbank Basin and then into the Ohai Basin. Such a trend is in agreement with the findings of both Bowen (1964) and Bowman et al. (1987) who suggest that rank increases gradually from southeast to northwest across the coalfield based on SpE data.

In summary, there are both lateral and vertical changes in rank within the sub-bituminous rank coals of Ohai Coalfield. There is an increase in rank down-hole and also a general increase from the southeast to the northwest. Because of correlation problems, individual seams cannot be compared between the Mossbank and Ohai Basins. The rank of Beaumont seams can rarely be assessed because most Beaumont coals contain too much mineral matter, however, Beaumont coal seams appear to be of similar rank to Morley seams. Petrologic character does not vary significantly through the sub-bituminous rank series. Therefore, although there is rank variation in Ohai Coalfield, this does not affect the petrographic constituents. Nor are changes in volatile matter dominantly controlled by rank in sub-bituminous coal (Suggate, 1959; Stach et al., 1982).

3.4.4 Temporal Changes in Chemistry

The major distinction between the Morley (Upper Cretaceous) and Beaumont (Eocene) coal seams is the high-volatile, hydrogen-rich nature of the Eocene coal. Beaumont seams generally have volatile matter values 5% higher than those of Morley coals. In addition, Beaumont seams have greater hydrogen/carbon (dmmf) ratios , both in low and high ash samples (Table 3.3). Both moisture and sulphur values are similar when compared between the Morley and Beaumont Coal Measures. In general major oxides in ash and mineralogy of Morley and Beaumont coal are similar with the exception that Beaumont coals may contain illite. This difference probably reflects the intensity of leaching of Morley mineral matter which dissolved clays and resulted in more uniform Morley coal chemistry.

Within the Morley Coal Measures (Cretaceous), seam intersections in horizon O/C2 have a slightly higher volatile matter value but otherwise moisture, sulphur, volatile matter, and total hydrogen, carbon and oxygen values do not vary significantly in any Morley seams suggesting that the geochemical conditions changed little during deposition of a number of stratigraphically distinct seams. Within Morley seams the only regular vertical trend in chemistry is that the ash content of coal generally increases towards partings and seam roofs and floors.

3.5 SUMMARY

In most respects the inorganic chemistry of both the Cretaceous Morley Coal Measures and the Eocene Beaumont Coal Measures are very similar. Of the organic chemical analyses, variations in volatile matter and the results of ultimate analyses are valuable for distinguishing between the Morley and Beaumont Coal Measures. For Morley coal samples, ash chemistry may be useful as a tool for interpreting the environment of paleomires whereas the results of volatile matter and specific energy analyses are useful in indicating rank variation within Ohai Coalfield. The major conclusions that can be drawn for chemical parameters are as follows:

1) Detrital minerals in Morley and Beaumont coal include rutile, illite, the majority of quartz and part of the kaolinite present. Carbonate and pyrite, as well as some kaolinite, are authigenic. Pyrite and authigenic kaolinite were formed syngenetically while carbonates probably have both syngenetic and epigenetic origins. Quartz which occurs in 'hard bands' is also epigenetic.
2) Clays in both Morley coal and sediments were altered by severe leaching in an organic-rich environment whereas the presence of illite and poorly-crystalline kaolinite in some Beaumont samples indicates that leaching was not always prevalent during the Eocene. Leaching of Morley mires may have reduced the amount of mineral matter in the peat.
3) Detrital material in both Morley and Beaumont coal seams was probably derived from low energy fluvial systems.
4) Coal rank increases both down drillholes and from the Mossbank Basin to the Ohai Basin. Despite rank variation, all coals are of sub-bituminous rank (from sub-bituminous C to A) therefore differences in rank are unlikely to be reflected in variations in petrologic character or in volatile matter.

CHAPTER 4

COAL PETROGRAPHY OF SEAMS IN THE MORLEY AND BEAUMONT COAL MEASURES AND INTERPRETATION OF MIRE ENVIRONMENTS

4.1 INTRODUCTION

The petrographic character of coal seams is widely used as a tool for interpretation of mire paleoenvironments as well as for evaluation of industrial utilisation of coal. Petrographic analyses generally include assessment of the nature and proportions of maceral components and microlithotypes as well as measurement of vitrinite reflectance. Vitrinite reflectance is commonly used as a rank parameter for bituminous coals although it is influenced by coal type in high as well as low rank coals (Newman and Newman, 1982; Newman, J. 1985a).

Although maceral analyses are the most common form of petrographic analysis, recent studies of Tertiary age coals in the South Pacific have shown a poor correspondence between coal lithotype, standard maceral composition and the behaviour of coal during beneficiation (Moore and Ferm, 1988; Moore et al., 1990). Therefore, an alternative petrographic approach was developed for Eocene coals of Kalimantan, Indonesia. This approach identifies the proportions of plant organs/tissues and matrix components in coal and relates them to the original plant components in the peat as well as measuring the size of all particles. Such a method of botanical analysis has been used in this thesis for Morley coal.

In this study, coal seam composite and ply samples were collected from the Morley and Beaumont Coal Measures in the Ohai and Mossbank Basins, Ohai Coalfield, in order to examine temporal changes between the two coal measures, within the Morley Coal Measures and within individual seams. In addition, in this chapter, petrographic variations are related to characteristics of the mire environments. Where appropriate, chemical data from Chapter 3 is integrated with petrographical data as is palynological information on both coal and sediments. Morley coal is also compared to seams of similar age which developed in other South Island coalfields in order to identify general differences or similarities between mires which developed coevally.

4.2 METHODS

4.2.1 Sampling

Coal available for petrographic sampling at Ohai is limited to the existing drill core samples (all coal samples from drill core were split and crushed shortly after drilling) and to underground mine faces in Wairaki No. 6 coal mine. Coal outcrop occurs in only three opencast mines in which few seams are exposed and all coal is weathered. Three types of petrographic samples were obtained:

1) Seventy-two pre-crushed (to <10 mm) composite seam (whole seam) samples from drill core.
2) Ninety-one pre-crushed (to <10 mm) serial ply samples from drill core.
3) Nineteen ply samples from two mine faces.

Composite samples were analysed to assess differences in maceral composition between Morley (Late Cretaceous) and Beaumont (Eocene) Coal Measures, and between coal in the Ohai and Mossbank Basins. Of the 72 composites obtained, 58 were from the Morley Coal Measures and 14 from the Beaumont Coal Measures (see Table 4.1 for a breakdown of ages and locations of samples).

Serial ply samples were obtained both from the Morley Coal Measures (83 plies from 3 drillholes) and from the Beaumont Coal Measures (8 plies from 2 drillholes). A breakdown of ply sample locations and ages is shown in Table 4.1. Analysis of ply samples was undertaken to determine within-seam petrographic variation for both Morley and Beaumont Coal Measures; the magnitude of within-seam petrographic variation could therefore be compared with variation between seams in each sedimentary horizon.

Underground sampling was restricted to the seam currently mined in Wairaki No. 6 (underground). Mine drives or access-ways at Wairaki No. 6 mine are usually 4 m to 6 m in height and at least 1 m of coal is left at the floor and roof, giving mine faces only 2 m to 4 m high for sampling. Samples were collected to compare macroscopic coal characteristics with microscopic character. At two locations in the mine (Fig. 4.1), the seam was divided into plies on the basis of changes in matrix brightness, the presence of dirty coal bands and small scale variations in the proportions of bright bands. From each ply, channel samples and blocks were collected. Two block samples approximately 3 cm by 5 cm in size were taken from within each ply, at different levels in the face, so that variation within plies could be assessed.

4.2.2 Macroscopic Analytical Methods

At the two underground sampling sites, macroscopic analysis assessed the proportions and sizes of bright bands in the coal. These bright bands form a high proportion of all coal at Ohai Coalfield (Fig. 4.2). To quantify the macroscopic texture of the coal, 10 seam sections were point-counted, 5 sections in the vicinity of each sampling site. All sections were within 120 m of the original sampling site (Fig. 4.1).

The sections were made by point counting at 2 cm intervals along a marked length of line laid down the face of the coal and fixed with pliable adhesive at either end. 2 cm was chosen as the interval size because the largest bright bands were rarely greater than 2 cm thick. Counts were made in 50 cm increments in order to compare the variability of counts within sections and because there was insufficient variation in macroscopic appearance for division of coal into plies which could be correlated between point count sites. For each mark on the line the presence/absence of a bright band greater than 0.5 mm in width was recorded and the widths of bands were also recorded. Only one count was made on each bright band, even if the band was greater than 2 cm thick. A size of 0.5 mm was chosen as the lower limit for macroscopic point counting for two reasons: firstly, the size of bands less than 0.5 mm are difficult to estimate visually and, secondly, the proportion of bands of this thickness can be estimated microscopically on block samples.

4.2.3 Microscopic Analytical Methods

Three types of petrographic analysis were performed:

1) Standard petrographic analysis on particle pellets from composite and ply samples.
2) Vitrinite reflectance on standard particle pellets.
3) Petrographic analysis of blocks, including standard maceral analysis, assessment of plant organ/tissue and matrix composition (botanical analysis) and also particle size distributions.

Standard maceral analyses on unetched particle pellets were performed for all composite and ply samples. Sample preparation for particle pellets consisted of crushing coal in an automated grinder to grains finer than 1 mm, setting the sample in epoxy resin and polishing the sample in general accordance with the American Society for Testing and Materials Method D 2797-85 (1987a). Point counts of particle pellets were accomplished by counting 500 points on one pellet. Spacing between points was 1 mm and the magnification used was X 640. Only one point was counted on any single grain of coal. It was determined that representative counts could be made on one pellet, rather than two pellets, after counts of 500 points were made on each of two pellets for five samples (Appendix G). The difference between the percentages of any single maceral component counted on either pellet was consistently less than 5%.

Sixteen macerals were recognised in the coal (Table 4.2 and Fig. 4.3). Identification of macerals was made according to the standards of the International Committee for Coal Petrography (1971) and Stach et al. (1982). In addition, corpocollinite was further differentiated on the presence or absence of surrounding telinite. In composite samples resinite which fluoresced in white light was differentiated from resin which did not. Also resinite in ply samples which fluoresced in white light was further divided according to the colour of fluorescence, green or yellow-brown.

All particle pellet samples from the Beaumont Coal Measures, as well as all high ash (> 10% ash) samples from the Morley Coal Measures, were counted using white- and blue-reflected light simultaneously. That is, when particles of low reflectance were under the cross hair, blue light was used to confirm whether the substance was a liptinite maceral or mineral matter. Blue light counts were found to be unnecessary for low ash (< 10% ash) particle pellets from the Morley Coal Measures, because examination of ten low ash samples showed statistically insignificant changes in liptinite counts from white light to blue light.

Reflectance analyses were performed on 60 particle pellet samples using a Zeiss UMSP 50 microscope. On each sample 100 measurements were made of the random reflectance of vitrinite macerals. The maceral type was recorded together with the reflectance reading. A sapphire standard (reflectance of 0.590) and two glass standards (reflectances of 0.930 and 1.005) were used for calibration and the system was recalibrated after every 25 readings.

Block sample preparation consisted of epoxy impregnating coal blocks in a 3 cm by 5 cm rectangular mould, then polishing the blocks on one face perpendicular to bedding using methods identical to those for polishing of particle pellets. After polishing blocks were etched for 5 to 10 seconds with a boiling solution of 25 g potassium permanganate and 5 ml of sulphuric acid in 100 ml of water. The blocks were then cleaned with a solution of 25 g sodium sulphite and 5 ml of sulphuric acid in 100 ml of water. This method is described in Stach et al. (1982) and by Stanton and Moore (1991), and has been used in New Zealand by Newman, J. (1988) and Quick and Moore (1991). Etching reveals fine cellular details and facilitates differentiation of individual vitrinite macerals. The detail visible in etched blocks, as compared to the appearance of unetched material, can be seen in Figure 4.2 (j) and (k).

Petrographic analysis of block samples involved point counts of maceral components, of botanical components and of the sizes of the botanical components. Counts were made on the etched block surfaces of 250 points in white light and a further 250 points in blue light. All traverses were made perpendicular to bedding with a point spacing of 1 mm.

Components were only counted once, even when they were wider than 1 mm. Point counts of botanical components were made using three levels of magnification; initially the component was viewed at X 50, but the magnification was increased to X 200 or up to X 500 for identification of small plant organs/tissues and matrix components. Data was collected in a computer programme described by Moore and Orrell (1991). This programme is a three-dimensional array in which the maceral, the botanical component in which the maceral occurs, and the size of the botanical component can be recorded simultaneously.

Macerals were described according to the International Committee for Coal Petrography Handbook (1971) except for the omission of the prefix "crypto-". In Table 4.2 maceral terms used for etched blocks are compared to maceral terms for unetched particle pellets. Botanical components were described in the style used by Moore and Ferm (1992) and Moore and Hilbert (1992) for petrographical analyses of Indonesian peat and coal. This system is similar in concept to that developed by Cohen (1973) and Cohen and Spackman (1977) for analysis of peat. Botanical analysis characterises the type of plant components which were originally incorporated in the peat. The components are divided into two main categories, plant tissues and organs which are groups of intact cells and matrix which consists of fragments of tissues and fungal material as well as amorphous humic gels.

Botanical analysis involves not only point counts of the plant components, but also size measurements of plant components. Size measurements were made of the longest dimension of the short axis of each component. The long axis was not measured because plant organs/tissues often extend beyond the limits of blocks and also because the apparent long dimension of plant organs/tissues is dependent on the angle at which blocks are cut, rather than being representative of the true long dimension of the parts.

The results of the maceral analyses on particle pellets were used to calculate tissue preservation indices (TPI) for all composite and ply samples. Calculation of TPI was developed by Diessel (1986) as a measure of paleo-degradation in peat and as a quick method of characterisation. Diessel included both vitrinite and inertinite macerals in his TPI index. However, in this thesis TPI is calculated separately for both vitrinite and inertinite maceral groups. Such a method of TPI calculation was employed to investigate whether oxidative degradation and non-oxidative degradation were occurring in similar or different mire environments. The formulae used here for calculation of the TPI of vitrinite, TPI(V), and the TPI of inertinite, TPI(I), are as follows:

$$\mathrm{TPI(V)} = \frac{\text{(telocollinite + telinite + corpocollinite in cell walls)}}{\text{(corpocollinite without telinite + desmocollinite + vitrodetrinite)}}$$

$$\mathrm{TPI\ (I)} = \text{(fusinite + semifusinite) / degradosemifusinite}$$

Inertodetrinite is not included in TPI(I) because this index is intended to show the variation in the proportions of inertinite retaining cellular structure and inertinite which has lost its cellular structure. The size of inertodetrinite makes it impossible to ascertain whether particles still have cellular structure. Values of TPI(V) and TPI(I) are listed in Appendix H (composite samples) and I (ply samples).

4.3 RESULTS

4.3.1 Petrography of Particle Pellets From Seam Composite Samples

The results of the standard maceral analyses for composite samples are given in Appendix H. The results were used to compare the petrology of the Morley and Beaumont Coal Measures and to examine the variation between and within the Ohai and Mossbank Basins. Table 4.3 shows a summary of this data for seams in the main coal-bearing sedimentary horizons.

The most significant contrasts in petrographic character are between the Morley and Beaumont Coal Measures (Table 4.3) in:

1) Proportions of the three major maceral groups (Fig. 4.4)
2) Proportions of resin which fluoresces green in white light
3) TPI(V) values.

Morley seams are generally composed of over 80% vitrinite, 5% to 15% liptinite and 5% to 8% inertinite, contain very little green fluorescing resin (0.1-0.2%) and have TPI(V) values which range from 0.7 to 2.0 but are usually less than 1.4. In contrast, Beaumont coal is composed of over 80% vitrinite but 10% to 20% liptinite and less than 1% inertinite, typically contains 1% to 3% green fluorescing resin and has TPI(V) values from 1.5 to 2.5.

The variations in total maceral group proportions in Morley coals are largely the result of variations in the percentages of suberinite and liptodetrinite, and semifusinite and inertodetrinite. In Beaumont coals the variation in the percentages of liptodetrinite have the dominant effect on the relative proportions of the three main maceral groups. The proportions of all individual liptinite and inertinite macerals, other than those mentioned above, do not differ significantly between either Morley or Beaumont seam horizons and composite samples. Within the vitrinite maceral group, the relative proportions of structured vitrinite (telocollinite, telinite, corpocollinite within telinite) and unstructured vitrinite (desmocollinite, vitrodetrinite, corpocollinite without telinite) vary as reflected in TPI(V), although the total percentage of the vitrinite group varies only between 80% and 90%.

The contrast between Cretaceous and Eocene coals is accentuated by the lack of variation between Morley seams in the two basins and in different sedimentary horizons. Although seams from all horizons in the Ohai Basin have lower TPI(V) values (ranging from 0.8 to 1.2 with an average of 1.0) than seams from all horizons in the Mossbank Basin (which range from 0.9 to 2.0 and average 1.2), no other general differences in petrography can be distinguished between the two basins. In the Ohai Basin seams from 3 Morley sedimentary horizons were investigated, O/C4, O/C3 and O/C2. These horizons are shown in Figures 2.8 to 2.11 and criteria for their recognition described in Chapter 2. Seam intersections in horizon O/C2 differs from seams in O/C4 and O/C3 because they contain more liptinite (mostly the result of increased proportions of liptodetrinite) and have lower TPI(V) values. In the Mossbank Basin, seams from five Morley sedimentary horizons were examined, M/S2, M/C2d, M/C2c-ii, M/C2b, M/C2a and M/C1 (Figs. 2.8, 2.9, 2.11, 2.12). Coal from the oldest horizon, M/C1, contains consistently higher proportions of liptinite and inertinite than coal from other Mossbank horizons and also has the lowest TPI(V) (as shown in Table 4.3).

The variation in Beaumont Coal Measures seams is difficult to assess, owing to the lack of correlation between seam intersections and also because only one Beaumont sample was obtained from the Ohai Basin. The Beaumont seams in the Mossbank Basin exhibit more variation in proportions of the vitrinite and liptinite maceral groups than do Morley seams (note the higher standard deviations in Table 4.3) and also generally exhibit more variable TPI(V) values.

4.3.2 Petrography of Particle Pellets From Ply Samples

Within the Ohai Basin, ply samples were obtained for one Beaumont seam in each of drillholes 346 and 375 and for six Morley seams in 4 different locations; four seams in drillhole 346, one seam in drillhole 357 and from 2 locations in one seam in the Wairaki No. 6 underground mine. In the Mossbank Basin ply samples were obtained for one Beaumont seam and four Morley seams in drillhole 375. Maceral analyses were performed on all Beaumont ply samples and all Morley samples from drillhole 346, the Wairaki mine and the seams in drillhole 375 from horizons M/S2, M/C2a and M/C1. However, for the seam in drillhole 357 and seams from horizons M/C2d, M/C2c-ii and M/C2b in drillhole 375, only a selection of ply samples was analysed because little petrographic variation had been found between ply samples in other seams. For the seams in drillhole 375 alternate ply samples were analysed. Ply samples from the seam in drillhole 357 which were petrographically analysed were selected to represent both median and extreme values of volatile matter.

Reflectance analyses were carried out for all ply samples from drillhole 346, all ply samples from drillhole 357 on which maceral analyses were performed, and from select plies in every seam intersection in drillhole 375. Both maceral and reflectance data for ply samples is listed in Appendix I.

The petrographic results from the ply samples show that there is more variation in maceral components within seams than occurs between seams in each sedimentary horizon or between seams in different sedimentary horizons (Table 4.4). The standard deviation of the total vitrinite percent for composite samples from all Morley seams in the Ohai and Mossbank Basins (4.0 and 2.6 respectively) are smaller than the standard deviations of vitrinite percent in individual seams (greater than 4.0). In addition, the standard deviation of vitrinite percent within seam horizons is usually less than 4.0 in the Ohai Basin and 2.6 in the Mossbank Basin. Similarly, the standard deviations of total liptinite and inertinite and for TPI(V) for all Morley and Beaumont seams in the Ohai and Mossbank Basins, and for seam horizons within these basin, are generally smaller than the standard deviations of these values for individual seams (Table 4.4).

The within seam vertical variations in maceral group proportions and TPI(V) values are shown in Figures 4.5 to 4.11. No petrographic parameters display vertical trends within Morley or Beaumont seams except for the trends in inertinite and TPI(V) in the Morley seams. Most parameters fluctuate in value, particularly in thicker Morley seams such as those in drillhole 357 and 375. In Morley seams there is a general decrease in the proportions of inertinite and an increase in TPI(V) values towards seam floors, roofs and partings, although these trends are often irregular and are not ubiquitous. Sykes (1985) documented variations in inertinite and TPI similar to the trends found in this study although his TPI values included inertinite macerals.

Four microscopic assemblages were identified in particle pellets of Morley coal (Fig. 4.12):

1. Unstructured vitrinite (desmocollinite) containing variable proportions of mineral matter interlayered with structured vitrinite (telocollinite, telinite with/without corpocollinite) as shown in Figure 4.12 (a).
2. Interlayered structured and unstructured vitrinite macerals (Fig. 4.12 (b)). Unstructured vitrinite is associated with liptinite macerals and some inertodetrinite but little mineral matter.
3. Unstructured vitrinite containing inertinite, including some degradofusinite (Fig. 4.12 (c)).
4. Semifusinite, inertodetrinite and degradofusinite predominant in a matrix of unstructured vitrinite (Fig. 4.12 (d)).

Assemblage 1 is found in high ash plies which may represent a parting or be adjacent to the seam floor or roof. Assemblage 2 is predominant throughout most Morley coal seams. Assemblages 3 and 4 differ only in the amount of inertinitic material in the coal. These assemblages are most common in plies away from partings or floors and roofs of seams.

Assemblages.in Beaumont seams vary only between high and low ash coal (Fig. 4.12 (e) and (f)). The high ash coal consists of structured and unstructured vitrinite set within mineral matter, which also contains high proportions of fine-grained liptinitic material. Clean Beaumont coals display interlayered structured and unstructured vitrinite. The structured vitrinite commonly contains suberinite and resinite and the unstructured vitrinite contains relatively little liptodetrinite as compared to high ash coal.

4.3.3 Relationships Between Petrographic and Chemical Parameters

The parameters reported here are the total maceral group proportions of liptinite and inertinite, the amount of degradation of the vitrinite and inertinite groups as shown by TPI(V) and TPI(I), reflectance, ash and volatile matter. These parameters were chosen because each displayed correlations when plotted against one of the other parameters. Relationships between parameters are described for composite and ply samples in both the Morley and Beaumont Coal Measures (Table 4.8) in order to characterise differences and similarities between the two formations. However, information on Beaumont coal is limited by the small number and generally high ash content of Beaumont samples.

Ash is a useful chemical parameter for correlation with petrographic composition. The total percentage of ash displays a positive correlation with liptodetrinite in Beaumont coal (Fig. 4.13) although no relationship in Morley coals. Ash and TPI(V) have a negative relationship in Beaumont coals but, in contrast, a weak positive relationship in Morley coals (Fig. 4.14). Beaumont coals contain very little inertinite (<2%) and therefore relationships between inertinite and other parameters are not significant. In Morley coals, although the correlation between ash and inertinite is poor, the proportion of inertinite is greater than 9% in only low ash samples (with one exception, 42/158, Fig. 4.15). In addition, although TPI(I) may range from 0 to 26 in low ash samples, in high ash samples TPI(I) is always less than 15. That is, the least degraded inertinite occurs in high ash samples although the greatest proportions of inertinite occur in low ash samples.

In addition to the relationship with ash described above, TPI(V) displays weak negative correlations with liptinite and inertinite (Fig. 4.16) in both Beaumont and Morley samples. That is, samples with high proportions of liptinite or inertinite also contain the most poorly preserved plant tissue. Ply samples from within Beaumont and Morley seams define parallel but separate negative trending fields in the plot of TPI(V) versus liptinite (Fig. 4.16 (a)).

Clearer relationships are seen between volatile matter and petrographic parameters when the ply samples are examined in sequence from top to bottom of seams rather then when samples from all seams are plotted together. In a plot of volatile matter against reflectance most Morley seams fall along negative trends (Fig. 4.17) although Beaumont seams display little variation in reflectance. Detailed examination of plots of volatile matter in Morley coal versus L, I and TPI(V) reveals that variations in volatile matter are also related to variations in the proportions of these three parameters. Rather than whole seams exhibiting a single trend of volatile matter related to L, I or TPI(V), sequential plies exhibit trends (Figs. 4.18 to 4.21, Table 4.9). When sequential plies are investigated, it can be seen that the relationships between volatile matter and L, I and TPI(V) are interrelated. Where there are large proportions of liptinite between plies (for example Fig. 4.19, plies 23 to 25, Fig. 4.20, plies 15 to 21, Fig. 4.21, plies 9 to 15), then there is a clear positive correlation of volatile matter with L but poor correlations of volatile matter with I and TPI(V). Conversely, if there are relatively high proportions of inertinite in plies (Fig. 4.18, plies 2 to 3, 3 to 13), then there is a strong negative correlation of volatile matter with I and weaker correlations of volatile matter with L and TPI(V). In sequential plies where volatile matter displays a negative or no correlation with L (Fig. 4.18, plies 16 to 18) together with a positive or no correlation with I (Fig. 4.19, plies 23 to 25), that is, the inverse correlations to those expected, volatile matter always displays a negative correlation with TPI(V).

4.3.4 Macroscopic Analyses of Mine Faces and Corresponding Microscopic Analyses of Block Samples

Macroscopic analyses were performed at the same 2 locations from which particle pellet and block samples were collected in Wairaki No. 6 underground mine (Fig. 4.1), in a seam from horizon O/C4. Macroscopic analysis estimated the proportion of bright bands in 50 cm increments at the mine face. Block samples were collected to investigate small scale changes within the seam. Comparisons were made between the results of the block samples and those of particle pellet samples from the same sample location.

4.3.4.1 Macroscopic Analysis of Mine Faces, Comparison of Maceral Analyses of Block and Particle Pellet Samples and Botanical Analysis of Block Samples

At the mine face bright bands greater than 1 mm in width were estimated to compose 23.6% ± 8% of the coal at location 1 and 24.6% ± 8% at location 2. No quantifiable vertical variation was observed in the 50 cm increment counts of bright bands although a slight increase in the proportion of bright bands in coal occurred immediately below and above partings. This observation concurs with that of Sykes (1985), who found greater proportions of bright bands adjacent to partings and near seam floors and roofs. Because macroscopic descriptions of mine faces were performed in the same localities as those from which block samples were taken, the results of the macroscopic descriptions can be related to the petrographic analyses of mine samples.

Results of the maceral analyses on particle pellet and block samples are similar except for the proportions of individual vitrinite macerals counted (Table 4.5, Appendices H and I). Counts of structured vitrinite were lower in the block samples than in particle pellets. This discrepancy is a function of the point counting technique in which the proportion of bright bands, composed mainly of structured vitrinite (96% telinite and corpocollinite and 4% suberinite), was estimated at the macroscopic level but could not be counted representatively on blocks. Very few bright bands greater than 1 mm in width occur on blocks, firstly because these bands are brittle and therefore blocks tend to break along bright bands. Secondly, because of the size of bright bands (1-40 mm in width), the proportion of bands in a ply cannot be accurately represented on 3 cm by 5 cm block faces. Therefore bright bands are under-represented on blocks and the structured vitrinite of which they are composed is under-represented in point counts on blocks as compared to point counts on particle pellets. However, when structured vitrinite counts from blocks are reproportioned to account for the megascopically determined proportions of bright bands, individual maceral counts for pellets and blocks are within 6% of each other (Table 4.5).

Botanical analysis of the Wairaki blocks revealed nine types of plant organs/tissues and ten botanical components in the matrix (Table 4.6). Botanical analytical results are listed in Appendix J. The different plant organs and tissues (Figs. 4.22, 4.23, 4.24) are

1) Seed
2) Leaf
3) Primary root (type 1)
4) Primary root (type 2)
5) Uncategorised stem/root with secondary growth
6) Secondary xylem tissue
7) Cork tissue
8) Unidentified plant tissue with well preserved cellular structure
9) Unidentified plant tissue with poorly preserved cellular structure.

In addition, oxidised plant organs/tissues can be distinguished from non-oxidised plant components in all the above categories. The plant components were differentiated on the basis of the plant tissue structure visible under the microscope.

Seeds are composed of tissue which has a distinctively high reflectance as well as unusually thick-walled cells (sclereids) which act as a protective layer for the embryo. They also have an outer cuticle and ring of palisade-like cells known as a Malpighian layer. Inner cells are small and thick-walled and are probably osteosclereids. The centre of seeds is generally filled with low-reflecting material, which is most likely to be fat or oil stored in the endosperm as the nutrient supply for the developing embryo. Seeds occur only in trace amounts in Morley blocks. They are frequently fragmented, only the outer layer of Malpigian cells or the Malpigian layers together with sclereids occurring.

Leaves generally have curved but regular outlines and are sometimes asymmetrical. They always occur in groups. The epidermis of leaves is a cuticle in which stomata can occasionally be observed. The inner tissue is often degraded.

The identification of primary roots was based on the predominance of thin walled corticle cells in these organs and the lack of any secondary tissue. These roots are characterised by their thin outer layer of cuticle and are distinguished from leaves on the basis of morphology (elongate to ovoid) and the frequent presence of very early secondary growth, in the form of two or three layers of cork cells (described in the following paragraph). This secondary growth also indicates the organs to be primary roots rather than stems as secondary growth is initiated in the central tissue rather than one cell layer below the epidermis, as in stems. The two types of primary stem/roots are distinguished on the basis of their internal tissue; the central tissue in stem/roots type 1 is dominantly cell wall material whereas in stem/roots type 2 the central tissue consists mostly of cell fillings. It is possible that these two stem/root types represent only different cuts through the same plant organs rather than different organs.

There are few diagnostic tissue characteristics which differentiate stems and roots with secondary growth from one another, therefore these are classed together. Stem/roots with secondary growth can be distinguished from other organs and tissues by the presence of cork cells and secondary xylem tissue. Cork cells can be identified by their rectangular shape and "filed" arrangement of cells, as well as their suberinised cell walls. Secondary xylem tissue is characterised by dense cell wall material with few cell fillings, except for fillings in ray cells. Cross-sections of stem/roots are elongate-oval in shape and possess an outer ring of suberinised tissue.

All plant tissue lacking diagnostic features was classed as 'unidentified tissue' and was assigned either to the 'well preserved' or 'poorly preserved' type, according to the amount of degradation of cellular material. Typical 'unidentified well and poorly preserved' plant tissue is shown in Figures 4.22 and 4.24.

The differences between plant organs and tissues (excluding seeds, which occurred in only trace amounts), in terms of their cellular components, can be shown in diagrammatic form (Fig. 4.25). Comparison of the tissue types which constitute the plant organ/tissue types found in the Morley Coal Measures blocks, shows that each plant organ/tissue has a characteristic composition. Leaves consist of cell walls (21%), cell fillings (42%) and an important component of cuticle (21%). Primary stem/roots types 1 and 2 both consist of cuticle, cell walls and cell fillings but stem/roots type 1 have a far greater component of cell walls (50% in type 1 as compared to 15% in type 2) whereas cell fillings form the major parts of stem/roots type 2 (62% in type 2 as compared to 5% in type 1). Cell wall material (36%) forms a major part of stem/roots with secondary growth, which also contain a large component of suberinised cell walls (25%). Secondary xylem consists dominantly of cell walls (88%) with few cell fillings (7%) and cork consists mainly of suberinised cell walls (82%) together with cell fillings (18%). Well preserved unidentified tissue is composed mainly of cell walls (63%) and cell fillings (26%). Poorly preserved unidentified plant tissue consists of cell walls (47%) together with 30% amorphous humic gel and 15% cell wall fragments which indicate that this tissue is highly degraded. Degradation in recognisable plant organs creating fragmented tissue or amorphous gel is more prevalent in stem/roots (12 to 25% degraded tissue respectively) than in leaves, xylem or cork (5%, 3% and 0.4% respectively).

Matrix consists of two major categories of material, amorphous and particulate (Table 4.6, Fig. 4.22 (g)). Amorphous matrix is matrix material within which grain boundaries cannot be distinguished at X 500. Within the particulate matrix category nine different components can be distinguished (Table 4.6.):

1) Fragments of cell walls.
2) Cell fillings unconnected to other tissue.
3) Cuticle.
4) Resin.
5) Spores.
6) Suberin.
7) Unidentifiable fragments of waxy or resinous plant material (cuticle, resin, spores, suberin).
8) Fungal material.
9) Unidentifiable fragments of oxidised plant tissue (mostly oxidised cell walls) and fungal material.

The total proportions of plant organs/tissues and matrix components in coal are similar for both sampling locations as are the percentages of individual plant organs/tissues and matrix components (Fig. 4.26). The major categories counted in blocks were: 1) macroscopic plant organs/tissues, 2) microscopic plant organs/tissues, 3) particulate matrix and 4) amorphous matrix. The most common plant organ/tissue type in both sites is xylem tissue which comprises 35% and 41% of the plant organs/tissues in the two sampling locations. The next most common plant organ/tissue, which is also the most common microscopic plant organ/tissue, is unidentified poorly preserved tissue which composes about 30% of the total plant organs/tissues in both sampling sites and about 60% of the microscopic plant organs/tissues. Stem/roots with secondary growth also form a significant proportion of the total organs/tissues (21% in site 1 and 15% in site 2). The most common oxidised plant organ/tissue type is well-preserved plant tissue which compose about 80% of the total oxidised material in both sites. The dominant matrix components are cell wall fragments (41% and 47% in sites 1 and 2 respectively) and amorphous matrix (40% and 31%). All other individual matrix components comprise less than 10% of the matrix.

No clear vertical trends are apparent in the proportions of plant organs/tissues or matrix components except in the proportions of bright bands which tend to increase towards partings. In addition, the plant organs and tissues to matrix ratio generally increases adjacent to partings in location 1 and away from the seam centre in location 2 (Fig. 4.27). The lack of trends may result from the fact that ply samples represent only the middle portion of the seam.

4.3.4.2 Macroscopic and Microscopic Size Data from Mine Faces and Block Samples

To compare the size distributions of plant organs/tissues and matrix components the widths of organs/tissues and matrix components were measured for all points counted on ten blocks from location 1. Bright bands (width > 0.5 mm) were measured in the macroscopic analysis while smaller components were measured microscopically. Similar size studies (Moore, 1990) show that the size distributions of organs/tissues and matrix components tend to be uniform within any single coal body therefore microscopic size measurements were made only on samples from one location. All size distributions are plotted on a phi scale as this was found by Moore and Ferm (1992) to be the most useful scale for displaying size relationships in coal components. Mean sizes of the plant organs/tissues and matrix components were determined using the method of moments calculation and are shown in Table 4.7.

The macroscopic plant organs/tissues, which are nearly all fragments of xylem tissue, display a normal size distribution (Fig. 4.28 (a)). The size of macroscopic plant organs/tissues measured in the coal face had a mean size of -1.7 Ø (3.2 mm) and ranged from -3 Ø to 1 Ø (8 - 0.5 mm). However, 0 Ø to 1 Ø (1 - 0.5 mm) plant organs/tissues are better measured in the microscopic counts because they are adequately represented on block faces and their widths are difficult to estimate visually in mine faces.

The distribution of sizes of microscopic plant organs/tissues is normal (Fig. 4.28 (b)), ranging from -3 Ø to 10 Ø (8 - 0.001 mm) with a mean of 3.5 Ø (0.09 mm). In addition, the size distributions of most individual microscopic plant organ/tissue types are also normal except for xylem and cork (Figs. 4.29, 4.30). All plant organ/tissue types on which more than 40 size measurements were made have a similar range of size distribution, encompassing 8 to 9 Ø classes. Xylem and stem/roots with secondary growth are the largest microscopic plant organs/tissues with means of 1.5 Ø (0.4 mm) and 2.2 Ø (0.2 mm) respectively. Primary stem/roots types 1 and 2 are slightly smaller, with means of 2.9 Ø (0.1 mm). Well preserved unidentified tissue is slightly larger than poorly preserved unidentified tissue (means of 3.4 Ø, 0.09 mm and 4.1 Ø, 0.06 mm respectively). Well preserved unidentified material has a very similar mean, whether oxidised (3.4 Ø, 0.094 mm) or unoxidised (3.5Ø, 0.088 mm). Cork cells have the smallest mean, 4.4 Ø (0.05 mm).

Particulate matrix components range in size from 2 Ø to 11 Ø (0.25 - 0.0005 mm) and have a mean of 8.8 Ø (0.002 mm) as shown in Figure 4.28 (c). The right skewed nature of the particulate matrix size distribution may be related to the limit of definition of size under the microscope rather than indicating an attribute of the population. Liu et al. (1982) has shown that when coal is examined under a transmission electron microscope, particulate matrix component widths of 0.125 to 0.064 μm (11 to 13 Ø) range can be measured. All size distributions of matrix components appear normal (Fig. 4.31) although the distribution of fungal material is not very clear. The nature of the size distribution of fungal material may result from a lack of size measurements (n = 11) or reflect that the group "fungal material" contains more than one population. The size distributions of matrix components have smaller ranges than those of plant organs and tissues, encompassing 5 to 7 Ø classes as compared to 8 to 9 Ø classes. The size distributions of all matrix components have mean values between 7 Ø and 9.2 Ø (0.008 mm and 0.002 mm). Cell fillings have the largest mean, 7.0 Ø (0.008 mm), spores and cuticles have means of 7.7 Ø (0.005 mm), oxidised fragments have a mean of 8.2 Ø (0.0034 mm), waxy/resinous fragments a mean of 8.4 Ø (0.0030 mm) and cell walls have the smallest mean, 9.2 Ø (0.002 mm).

When the size distributions of macroscopic and microscopic plant organs/tissues and particulate matrix are plotted together (Fig. 4.28 (d)), three distinct but overlapping populations can be clearly seen. The matrix distribution has a more pronounced mode than the size distributions of macroscopic and microscopic organs and tissues.

4.4 DISCUSSION

4.4.1 Petrographic and Chemical Parameters Used for Determination Of Original Morley and Beaumont Mire Environments

Various petrographical parameters can be used as indicators of particular depositional regimes in the paleo-mire environment. Such parameters include the proportions of maceral groups and individual macerals present in coal, tissue preservation indices calculated from maceral proportions, maceral assemblages, microlithotypes and volatile matter. Palynological data can also prove useful for inferring the character of the mire paleo-flora in association with petrographic data The following discussion considers the applicability of the above parameters for interpreting Ohai Coalfield paleo-mire environments.

4.4.1.1 Liptinite Macerals

The proportion of liptinite macerals in coal may be related to a number of environmental factors. For example, some plants produce more liptinitic precursors than others, such as trees which shed bark (suberinite) regularly or ferns which produce numerous spores (sporinite). Alternatively, liptinite macerals may be concentrated in conditions of intense or rapid microbial decay because liptinitic material is resistant to decay (Thiessen and Johnson, 1930; Buckman and Brady, 1970). In addition, liptinite precursors may be sorted hydrologically, forming a detrital layer.

Morley coals generally contain 6% to 11% liptinite although plies may contain up to 20% liptinite. There are a few instances where liptinite rich layers are observed and in most of these liptinite is associated with mineral matter, indicating that these layers were deposited by flood event. However, plots of liptinite against ash for composite and ply samples display no correlation, therefore it is likely that detritally derived liptinite is rare in Morley coals.

There is a general trend of decreasing TPI(V) with increasing liptinite (Fig. 4.16 (a)) in Morley coals, that is, samples containing the most liptinite tend to contain the most degraded tissue. This relationship suggests that concentration of liptinite by microbial degradation was one of the factors which influenced the proportion of liptinite in Morley coals. The three outlying points in Figure 4.16 (a) are high ash coals which contain liptinite associated with mineral matter, that is, liptinite which is probably of detrital origin.

Beaumont coals characteristically contain over 10% liptinite and often up to 30%. Hydrological concentration of liptinite associated with flood events was probably common in Beaumont mires. This is indicated by the positive correlation of liptodetrinite (the dominant liptinite maceral) with ash. In addition, liptodetrinite is particularly common in mineral-rich layers of the coal.

4.4.1.2 Inertinite Macerals

The origin of inertinite has been attributed by most authors to either charring or microbial or aerial oxidation, with the exception of sclerotinite which has an originally melanin rich composition and therefore high reflectance. There is little evidence that charring, microbial or aerial oxidation of Beaumont peat occurred because Beaumont coal contains little inertinite (1% of total macerals). However Morley coals consist of varying proportions of inertinite, usually 3% to 8% but up to 20% in some plies.

There is no lack of studies which show that charring of plant tissue will create material of inertinitic appearance, with a reflectance comparable to fusinite or semifusinite. Examples are Scott (1989), and Jones et al. (1991). Fires in mires may affect living plants, surface litter or peat material. Cohen et al. (1987) found that when the surface layer of peat is burned, the oxidised fragments occur in a matrix of unoxidised tissue. In contrast to this, when the surface peat layer is burned, entire bands rich in oxidised tissue are formed. If charring created inertinite in Morley coals, then the fire burnt only the surface vegetation rather than the peat. Evidence for this supposition includes:

1) The lack of fusain bands in Morley coal. Fusain bands are indicative of widespread charring of the peat surface.
2) No oxidation of macroscopic plant organs/tissues (bright bands in coal). Burning of all peat material, both macroscopic and microscopic, would be expected if fires occurred.
3) Inertinitic material is found within a matrix of desmocollinite.

In contrast to the amount of research done on oxidation of plant material by charring, few studies have shown that inertinitic material can be produced by microbial degradation or aerial oxidation; Cohen and Spackman (1980) and Cohen et al. (1987) observed increased reflectance of cellular material around sites of fungal attack in peat and Styan and Bustin (1983) found fungal sclerotinite associated with degradofusinite and pyrofusinite in Canadian peats. Both these workers also noted darkening of peat tissues which were exposed to air at the mire surface. Stanton (pers. comm., U.S. Geological Survey, Reston, VA, U.S.A.) has found that wood rotted in a compost heap has a microscopic appearance similar to that of charred wood. Beck et al. (1982) observed that the microstructure of fusinitised *Callixylon* wood contained features which are not seen preserved in charcoal produced at over 300°C and concluded that fusinitisation of wood probably has several origins, as well as fire. Because of the limited evidence that microbial oxidation can create inertinitic material, studies such as that of Schopf (1975) rely on an absence of evidence for combustion to conclude that inertinite was formed by microbial oxidation. Evidence that much of the inertinite in Morley coals was produced by microbial attack or aerial oxidation include the following:

1) Oxidised microscopic plant organs/tissues and oxidised matrix material have identical size distributions to non-oxidised plant organs/tissues and matrix (Fig. 4.30). Scott (1989) found that inertinitic plant organs/tissues created by charring have a size distribution with a smaller mean size than the size distribution of non-charred plant organs/tissues in the same coal.

2) Degradosemifusinite is found together with concentrations of semifusinite and inertodetrinite. There are no reports of charring producing inertinitic material of degraded appearance. The occurrence of degradosemifusinite, which has no remaining cellular structure, in coal containing large amounts of inertinite (semifusinite) with good cellular structure, suggests that the modes of formation of the inertinite in this coal may be related.

However, fusinite is not generally found associated with other inertinite macerals and may well be the result of charring.

The fragmented nature of inertodetrinite in Morley coals may have resulted from physical breakdown of pre-oxidised material by root penetration or during compaction. Inertodetrinite is often ascribed to physical breakdown during transport of macerals, however there is no association of inertodetrinite with mineral matter, nor are there inertodetrinite rich layers of detrital appearance which would support a transport origin.

The proportion of inertinite in Morley coals generally increases towards seam centres and away from partings although this pattern is neither regular nor ubiquitous. The Morley mire environments in which greater proportions of inertinite were produced were probably relatively dry as compared to the intervals in which little inertinite formed. Production of fire-derived inertinite is more likely to have occurred during dry periods as is aerobic oxidation of plant tissue. Therefore it appears that, as mires developed, periods of low water table became more common. An increase in microbial oxidation indicates a more oxygenated environment (Cohen et al., 1987) which could have resulted either from lowering of the mire water table or from introduction of more oxygenated water. The abundance of inertinite in low ash samples suggests that drying of the mire, rather than flooding, resulted in increased microbial oxidation. In addition there is an increase in the products of fire/oxidative decay, that is, inertinite, towards the middle of seams and away from partings. If flooding resulted in production of inertinite then the proportions of inertinite would be expected to increase towards, rather than away from partings.

4.4.1.3 TPI

The amount of degradation of plant material in peat is indicated by tissue preservation indices. Although Diessel (1986) included inertinite in his original TPI equation, in this thesis separate TPI equations were designed for vitrinite (TPI(V)) and inertinite macerals (TPI(I)) to see whether oxidative and non-oxidative degradation were occurring in the same mire environments. In fact, in Morley coals preservation of vitrinite macerals is poorest in high ash coals whereas preservation of inertinite macerals is best in high ash coals. Therefore it does not seem useful to include both inertinite and vitrinite in a TPI for Morley coals although as Beaumont coals contain less than 2% inertinite, inclusion or exclusion of inertinite macerals does not significantly affect Beaumont TPI values. Some authors, such as Sykes (1985), include liptinite macerals in TPIs. The difficulty in incorporating liptinite macerals into a TPI is that maceral analyses do not distinguish between liptinite macerals occurring in intact plant tissue and those "floating" in the matrix. Therefore, a point count system with separate categories for liptinite macerals in tissue and in matrix is required if liptinite macerals are to be included in a TPI.

The degree of non-oxidative degradation of plant tissue reflected by TPI(V) is related to the type and amount of microbial activity in peat as well as to the type of plant tissue which is being degraded and also the rate at which plant material is accumulating. The amount of microbial activity in peat is affected by environmental factors such as the level of the water table, pH and nutrient supply and temperature (which is related to climate), all of which also affect mire flora as regards both the type and stature of the vegetation. Therefore changes in TPI(V) cannot be related to changes in any single environmental parameter.

Clymo (1983) noted that degradation is most rapid in the surface layers of peat, that is, in the zone of aerobic decay which lies above the water table. He found that degradation rates slowed below the water table. Furthermore, degradation of lignin cannot occur in an anaerobic environment (Zeikus, 1978) therefore once woody material is buried below the water table it will not be further degraded. A rise in the water table, or rapid burial of peat by sedimentation or during rapid accumulation of plant material, can submerge peat below the table and therefore decrease the degree to which plant tissue is degraded, increasing TPI(V). Conversely, a drop in the water table or a slower rate of accumulation of plant material can increase in the degree of decay in a peat layer, decreasing TPI(V) In addition, some root material may grow down into the zone of anaerobic decay, below the level of water table fluctuation (approximately 25 cm). This material will not be subjected to the rapid decay which occurs in the aerobic zone and therefore will raise the TPI(V) of peat. The greater the number of roots penetrating deeply into the peat, the higher TPI(V) will be.

Anderson (1983) documented rapid peat accumulation during the early stages of mire development followed by declining peat accumulation as mires age. Rapid peat accumulation during early mire development is probably related to the availability of nutrients in the mire and thus to the types and sizes of plants growing in the mire. If the rate of peat accumulation was the dominant control on the rate of decay in a mire, the degree of degradation would be lowest during initial mire development (resulting in high TPI(V)) but would increase as the mire aged (decreasing TPI(V)). Furthermore, if nutrient supply or acidity had an important effect on rates of decay by limiting the types and sizes of flora or by affecting microbial activity, an increase in TPI(V) would be expected following a flooding event in which nutrient-rich material would be introduced to the mire and acidity reduced by the influx of fresh water.

In Morley coals, TPI(V) increases towards the floors and roofs of seams and towards partings, as do the numbers of bright bands in coal. These increases may all be the same trend as the bright bands consist mostly of structured vitrinite and constitute a considerable proportion (about 25%) of coal. However, Figure 4.27 shows that the ratio of microscopic plant organs/tissues to matrix (that is, the coal components excluding the bright bands) also increases towards partings (location 1) and away from the seam centre (location 2) (i.e., the ratio varies in the same way as proportions of bright bands and TPI(V)). Two locations provide insufficient data to draw firm conclusions from; however, it seems that both the amount of bright bands and the preservation of the microscopic tissue may increase together. In contrast, some studies of peat, such as Esterle and Ferm (1990) have found that where the amount of woody tissue in peat increases, the preservation of the matrix decreases.

Increases in TPI(V) and proportions of bright bands are often associated with an increase in the mineral matter content of the coal, particularly above seam floors and partings. The changes in TPI(V) can be divided into two types, increased TPI(V) a) above floors or partings and b) below roofs or partings. The increased TPI(V) above floors and partings may be related to the changes in nutrient supply and mire chemistry associated with flooding (as described above). Alternatively, flooding associated with deposition of partings may have raised the water table, reducing the degree of decay in peat. The increases in TPI(V) immediately below seam roofs and partings may be attributed to either of two mechanisms. Firstly, gradual flooding of the peat mire could have slowly raised the water table and nutrient levels, thus raising TPI(V). Secondly, rapid burial of the mire by flood sedimentation may have left the peat permanently below the water table, cutting short the normal period of degradation (as already discussed with reference to Clymo (1983)). Coal seams generally grade upwards into carbonaceous mudstone therefore, in the majority of cases, mire death was probably the result of gradual flooding.

For Morley coals, the inference that high TPI(V) values were created by raised water tables is supported by the variation in inertinite in seams. Inertinite in these coals is thought to be indicative of relatively dry periods in the mire (section 4.4.2). Inertinite levels, and therefore relative dryness in the Morley mires, increase away from partings and seam floors/roofs, that is, inertinite indicates that mires were driest in their centres, where low TPI(V) values occur.

Beaumont coals display a relationship between ash and TPI(V) inverse to that seen in Morley coals, that is, TPI(V) increases as ash content decreases (Fig. 4.14). Beaumont coal which contains little mineral matter probably developed in areas remote from fluvial activity, possibly adjacent to shallow lakes (Chapter 2). When development of the peat ceased, the peat remained in an area with a high water table (adjacent to lakes) and was therefore not substantially decayed, resulting in a high TPI(V). Beaumont coals which are mineral matter rich originated as peats that were frequently flooded and some organic material in these peats may also have been transported into the mire during flooding. It is possible that the relatively low acidity and high nutrient levels of the flood water promoted microbial activity, creating more degraded peat.

4.4.1.4 Maceral Assemblages

Maceral assemblages are another characteristic of coals used for interpretation of paleo-mire environment (Raymond, 1985; Newman, J. 1987a). In Morley coals the four maceral assemblages identified are common to all coal seams. Assemblage 1 has a detrital appearance, owing to the quantity of mineral matter within it, and is found associated with high ash zones in seams or at the base or top of seams. Assemblage 1 indicates that flooding of coal and input of detrital matter occurred. Assemblage 2 is the "normal" assemblage of Morley coals and consists of layers in which plant tissue has been degraded by varying amounts. Assemblages 3 and 4 are found in plies which are relatively inertinite rich, towards seam centres and away from partings, and the inertinite in these assemblages indicate that conditions conducive to burning/microbial oxidation occurred. These assemblages may represent periods of better drainage within the mires. Maceral assemblages within Beaumont coals are not very variable and are therefore not useful for distinguishing changes of paleoenvironment within Beaumont mires.

The use of maceral assemblages as a tool for paleoenvironmental analysis is limited by the small particles in coal pellets. Because of the small grain size, the association between different assemblages cannot be viewed and therefore the relationships between the different assemblages, and the environments they are inferred to represent, cannot be assessed.

4.4.1.4 Volatile Matter

Volatile matter has been used extensively as an indicator of paleo-mire environment by Newman, J. (1985a, b, 1987c, 1989). In Morley and Beaumont Coal Measures it is apparent that variations in volatile matter are controlled by the proportions of maceral groups as well as by vitrinite chemistry as reflected in TPI(V) (Figs. 4.18 to 4.21, Table 4.9). The complexity of the controls on volatile matter as described in sections 4.3.3 prevents correlation of volatile matter variation with change in the paleo-mire environment. Rather, environmental variations in the paleo-mires are best interpreted from other parameters, such as maceral group proportions and macroscopic coal character.

4.4.2 Temporal Changes in Mire Environment

Temporal changes in mire environment at Ohai Coalfield have been assessed at three different scales:

1) From the Late Cretaceous to the Eocene.
2) Throughout the accumulation of the Morley Coal Measures.
3) Changes during the development of individual Morley seams.

The changes in mire paleoenvironment from the Cretaceous to the Eocene are marked, whereas mire environments changed relatively little during Late Cretaceous peat accumulation or during individual seam development.

4.4.2.1 Differences between Late Cretaceous (Morley) and Eocene (Beaumont) Mires

Morley and Beaumont coal can be distinguished on the basis of:

a) Ash values (Chapter 3).
b) Maceral group proportions.
c) Percentages of resinite which fluoresces green in white light.
d) TPI(V) values.
e) Palynology (Appendices K and L).

The high proportions of ash in most Beaumont coals suggests that many Eocene mires were frequently flooded. This flooding indicates that the surfaces of the Eocene mires were low-lying, that is, little raised above the surrounding substrate. Such mires are referred to as "topogenous" (Polack, 1950). The lack of inertinite in Beaumont coal may also suggest perpetually wet conditions in the mires. In contrast, Morley mires were infrequently flooded (most Morley coal is low ash) and may have been raised above the surrounding area to some degree (Chapter 2). The relative abundance of inertinite in Morley coals is further supporting evidence that, at times, the water table in Morley mires dropped and flood events were rare. The water supply for mires raised above the surrounding substrate is from rainwater only (the "ombrogenous" mires of Polack (1950)), therefore flooding of mires is rare.

In comparison with Morley coal, Beaumont coal contains more liptinite. These increased proportions of liptinite reflect raised percentages of suberinite and liptodetrinite as well as the presence of green-fluorescing resinite in Beaumont coal. The liptodetrinite in Beaumont coal was introduced during the frequent flood events. The increase in suberinite from the Cretaceous to the Eocene coal may indicate, together with the different resin type in Beaumont coal, that mire floras in the two ages may have been dissimilar. This inference concurs with the differences in palynology of the Cretaceous and Eocene sediments and coal found in all palynological analyses of the Morley and Beaumont Coal Measures (Appendix

K). The Morley flora was probably dominated by gymnosperms, particularly *Phyllocladidites mawsonii,* which occurred with lesser components of pteridophytes and angiosperms. In the few available samples of Eocene coal, gymnosperm pollen and angiosperm pollen are both important components but pteridophytes spore counts are very low.

Higher TPI(V) values in Beaumont coal, as compared with Morley coal, indicate that conditions in the Morley mires were probably more conducive to decay than in the Beaumont mires. The greater decay in Morley mires may have been the result of relatively low water tables or because of low peat accumulation rates as poor nutrient supplies limited plant growth. Increased decay can also reflect the presence of more degradable vegetation, although this is probably not the case for Morley coal. Gymnosperms were dominant in Morley mires but in Beaumont mires both angiosperms and gymnosperms were important. Gymnosperm lignin is far more resistant to decay than is angiosperm lignin (Faix et al., 1985), therefore if floral type controlled the amount of decay in peat, Morley peat would have been <u>less</u> degraded than Beaumont peat as it probably contains a greater proportion of gymnosperm tissue.

In summary, the contrast between the character of the Morley and Beaumont coals reflect differences in the frequency with which mires were flooded and related mire water table fluctuations as well as major differences in mire flora. Newman (1989) suggests that climate may have been an important influence on New Zealand paleo-peat character and that during the Cretaceous temperatures were cooler than in the Eocene. A change in climate can result in variations in environment including rainfall and flora and therefore differing climates in the Cretaceous and Eocene may have been the overriding factor influencing peat type. However, although climate must be considered, data available at present is not sufficient to indicate reliably the nature of New Zealand paleoclimates and the influence of paleoclimate on the peat.

4.4.2.2 Changes in the Nature of Mires During Accumulation of the Morley Coal Measures

Proportions of maceral groups and individual macerals are very uniform in all Morley seam horizons. In addition, all seams contain very similar pollen assemblages (data in both Warnes, (in prep.) and Appendix L). The only differences in maceral proportions between coal seams in different sedimentary horizons is the higher liptinite content and lower TPI(V) of coal seams in the oldest 'C'-horizons studied in each sub-basin (horizons O/C2 and M/C1). The greater proportions of liptinite in these seams have resulted from greater tissue degradation in these mires than in later mires as is suggested by the low TPI(V) values. More advanced degradation probably resulted from these early mires having generally low water tables. Further evidence that mires in M/C1 were relatively dry is the high inertinite content of the coal in this horizon.

The other significant difference between Morley seams is that Mossbank coal seams generally contain more mineral matter, partings and higher TPI(V) values than do Ohai seams. These differences indicate that Mossbank mires were more subject to inundation by sediment-bearing water than were Morley mires. Inundation of the mires may have raised the water table, thus reducing the period in which peat was aerobically decayed. Alternatively nutrients supplied from the floodwaters may have promoted woody plant growth, thereby increasing the amount of decay-resistant tissue in the mires.

4.4.2.3 Changes in Mire Character During the Development of Individual Morley Mires

The high vitrinite character of Morley seams precludes dramatic variations in petrographic character within seams. The only regular variations identified are general increases in TPI(V) (and bright bands in coal) together with ash, and corresponding decreases in inertinite towards the seam floors, roofs and partings. These variations, as discussed in sections 4.4.2 and 4.4.3, reflect variations in swamp chemistry, nutrient supply and water table which were probably related to flood events during mire development and the nutrient-rich substrate on which mires developed. Early mire growth was often rapid and tissue preservation good because water tables were high. As mires developed they probably became drier and plant growth rates and stature may have diminished because nutrient supplies declined and acidity increased. Mire death was probably slow in most cases because the majority of coal seams grade up into carbonaceous mudstone at their roofs. The good preservation of tissue towards seam roofs may reflect a gradual rise in water table and possibly an increase in nutrient supply resulting once again, as at the base of seams, in a woodier flora. The fact that the variations in inertinite and TPI(V) can be identified in most seams but not in every case suggests that development of individual mires, although similar, was not identical.

Palynology indicates that substantial changes in vegetation occurred from non-peat forming communities to mires; mire floras also changed as mires developed (Warnes, (in prep.) as discussed in Appendix K). Non-peat forming communities were angiosperm dominated but mires were gymnosperm dominated. Changes in mire vegetation that can be inferred from the palynology are a general decrease in floral diversity as mires developed and an increase in the proportion of *Phyllocladidites mawsonii* in the flora. Decreasing nutrient supplies and increasing acidity may have controlled these vegetational changes. However variations in the palynology of coal (Appendix L) cannot be directly related to variations in petrographic character of Morley seams. This is not unexpected because Hagemann and Wolf (1987) found changes in water table to be the dominant control on coal petrography, overprinting any changes in coal character resulting from floral succession in Rhenish brown coal.

The small scale petrographic variations seen in maceral groups in ply samples (Figs. 4.18 to 4.21) are evidence that mire character changed throughout seam development but not necessarily in a regular fashion or, perhaps, in a way which did not produce regular variation in the proportions of most maceral precursors. It is possible that an alternative type of petrographic study, such as botanical analysis, might reveal small scale changes in paleoenvironment which are not evident from maceral analysis. Alternatively, the character of these mires may have varied at a level that cannot be quantified by the type of petrographic analyses commonly undertaken at present.

4.4.3 Petrographic Comparison of Morley Coal with Coal Seams from Other New Zealand Coalfields

During the Cretaceous a number of sedimentary basins developed on the New Zealand landmass. The Paparoa Coal Measures at Greymouth and Pike River Coalfields and the Taratu Formation in the Kaitangata Coalfield accumulated at approximately the same time as the Morley Coal Measures at Ohai Coalfield. Deposition of the Paparoa Coal Measures and Taratu Formation also continued into the early Tertiary. In this section the petrographic characteristics of coal seams in three of the upper members of the Taratu Formation, in the Rewanui Member of the Paparoa Coal Measures at Greymouth Coalfield, and in Members 3 and 4 of the Paparoa Coal Measures at the Pike River Coalfield, are compared with the petrography of Morley seams. The discussion is limited to a broad comparison of the general petrographic characteristics of the coals under consideration and does not attempt to compare detailed petrography of the coals. The general conclusions here are intended to guide any petrographic studies in the future which are specifically aimed towards comparison of Cretaceous coal measures in New Zealand.

In addition to comparison of Morley coals with other Cretaceous coals, the petrography of Morley block samples is compared to the petrography of Eocene coal from the Brunner Coal Measures in Pike River Coalfield. The reason for this comparison is principally because no similar botanical analysis has yet been completed on any other New Zealand coals. However, Morley and Brunner coals are of markedly different texture and it is shown that botanical analysis can be used to investigate the reasons for their dissimilarities.

4.4.3.1 The Penman, Benhar and Mt Wallace Members of the Taratu Formation, Kaitangata Coalfield

Kaitangata Coalfield is located 80 km southwest of Dunedin (Fig. 4.32) and occupies an area of about 250 square kilometres. Raymond (1985) investigated coal seams in the Benhar-Lovells Flat area, west of the Castle Hill Fault, in which all sedimentological information is from drillhole data. Raymond looked at coal seams in three of the uppermost members of the Taratu Formation: the Penman (youngest), Benhar and Mt Wallace Members. The Late Cretaceous Penman and lower part of the Benhar Members developed within northeast trending, tectonically controlled half-grabens but the Early Paleocene upper Benhar and Mt Wallace Members were deposited across a wider area (Raymond, 1985).

Coal seams are all lignite (moisture values from 40% to 49% and volatile matter from 38% to 51%). In the Penman Member only three major seams occur, from 2 m to 10 m thick. In the Benhar Member seam thickness varies laterally; most seams are less than 2 m thick but may be up to 5 m thick, and numerous seams are found in each drillhole. Seams occur only in the upper 20 m to 30 m of the Mt Wallace Formation and are 4 to 9 m thick in some drillholes but thin southward to 1 to 2 m. Penman seams are usually low ash, Benhar seams produce variable proportions of ash and Mt Wallace seams are usually high ash (Table 4.10). Macroscopically, both Penman and Mt Wallace coals, and some Benhar coals are bright with occasional bright bands from 1 mm to 5 mm thick. Other Benhar coals are bright with up to 30% bright bands which are all less than 1 mm thick. The microscopic character of Penman, Benhar and Mt Wallace coals is shown in Table 4.10 and Figure 4.33. All coals are vitrinite dominated although some Benhar and all Mt Wallace coals contain over 20% inertinite. The TPI values of Penman coals generally vary from 0.7 to 1.4, Benhar coals exhibit very variable TPI values (from 0.2 to over 4), and Mt Wallace coals typically have TPIs below 0.6.

The macroscopic character of Morley coals is unlike that of Kaitangata coals because Morley coals contain numerous thick (1-40 mm) bright bands which typically compose between 20 % and 30% of the coal. However, the petrography of Morley coals (Table 4.10) is similar to that of Penman and the less inertinite rich Benhar Member coals. Although inertinite rich plies, containing 20% inertinite or more, occur within Morley seams, very few whole seam samples contain over 10% inertinite. This is in contrast to Mt Wallace seams in which inertinite commonly composes over 20% of seams. In particular, bands of detrital inertodetrinite associated with mineral matter are common in Mt Wallace and some Benhar seams but are never seen in Morley coals. Microscopic inertinite rich layers in Morley coals consist of mixed semifusinite, degradosemifusinite and inertodetrinite and do not contain any visible mineral matter; similar inertinite rich layers are seen in some Benhar coals which contain over 10% inertinite. The presence of the inertinite rich and mineral matter layers in the Kaitangata coals indicate that the mires underwent more periods during which the water table was low and also more redeposition of macerals occurred within the mire, as compared to Morley coals. However, the interlayered texture of structured and unstructured vitrinite, which is seen in Penman and inertinite poor Benhar coals, is typical of Morley coals.

4.4.3.2 The Rewanui Member of the Paparoa Coal Measures, Rapahoe Sector of Greymouth Coalfield

Greymouth Coalfield is located on the West Coast of New Zealand and the Rapahoe Sector comprises a 4 km by 8 km area in the west and southwest of the coalfield (Fig. 4.34) where both drill core and outcrop information are available. In Greymouth Coalfield the Paparoa Coal Measures are divided into 7 members, one of which is the Rewanui Member. Coal seams in the upper third of the Rewanui Member were documented by Newman, J. (1985a, 1987a). From findings on seam geometry and petrography, Newman recognised two types of coal seams with specific geographic distributions. In the south of the sector, the few seams which developed are commonly over 10 m thick. In contrast, in the north seams are abundant, vary rapidly in thickness and are separated by up to 30 m of fine-grained fluvial sediment.

Most coal in the Rapahoe Sector is of high volatile bituminous-C to B rank. The coals have generally uniform maceral character, comprising over 80% vitrinite and 3% to 10% liptinite and inertinite. However, Newman, J. (1985a, 1987b) divided the seam intersections into four types based on petrographic and chemical character and related these coal types to floral and drainage characteristics of the paleo-mires. The four coal types are characterised in Tables 4.11 and 4.12 and Figure 4.35 (a). Type I contains more resinous and suberinitic material, sometimes associated with layers of mineral matter, than other types and Newman inferred that it was formed from coniferous vegetation which grew adjacent to fluvial channels. Type II contains thin inertinite rich horizons which may indicate periods of better drainage in the mire. Type III is typified by an assemblage of fragmented macerals which are sometimes associated with mineral matter. The fragmented macerals were probably derived from flooding of peat by streams within the mires. A small additional category, Type IV, consists of micro-laminae of detrital macerals, including abundant inertodetrinite, and is thought to have been deposited in a subaqueous lake margin environment.

The general maceral composition of Rewanui coals Types I, II and III is very similar to the composition of Morley coals (Fig. 4.35 (a)). However, although the maceral assemblages seen in coals Types II and III are common within Morley seams, the maceral assemblage in coal Type I is more similar to Beaumont coals than Morley coals, particularly in the presence of more resin. Coal of type IV contains more inertinite and less liptinite than most Morley seams and has a texture unlike any seen in Morley coal. The lack of variation in Morley coal as compared to Rewanui coal suggests that both the flora and the geographic setting of Morley mires was more uniform than that of Rewanui mires. The flora in Morley mires does not appear to have varied adjacent to the low energy channels draining the mires (unlike Rewanui Type I) and Morley mires did not generally form in lacustrine environments (no coal of Rewanui Type IV).

4.4.3.3 Members 3 and 4 of the Paparoa Coal Measures, Pike River Coalfield

Pike River Coalfield lies 40 km northeast of Greymouth (Fig. 4.34) in a remote area in which sedimentological data is mostly from outcrop. The stratigraphy and sedimentology of Paparoa Coal Measures at Pike River Coalfield have been described by Newman, J. (1985a) and Newman and Newman (in press). The sequence in this area is divided into six members but only Members 3 and 4 contain coal. Seams in Member 3 are up to 10 m thick, are less than 0.5 km in lateral extent and are commonly interbedded with carbonaceous mudstone. In contrast, seams in Member 4 are generally less than 4 m thick, are cleaner and more extensive than Member 3 seams and are interbedded with coarse grained sediments. The macroscopic appearance of Member 3 and 4 coals is bright with few bright bands.

All coal from Members 3 and 4 is of high volatile bituminous A rank. The petrography of these coals is shown in Table 4.13 and Figure 4.35 (b). On the basis of coal petrography and chemistry, seams in Member 4 can be divided into those from the south and those from the north. The seams in the northern part of Member 4 are very similar to coal in Member 3; both contain common detrital layers which are mineral matter-rich, although Member 4 seams contain less mineral matter than Member 3 seams. Coals in the southern part of Member 4 contain little mineral matter and few detrital layers and often exhibit horizons rich in inertinite. All coal seams from Members 3 and 4 contain poorly preserved vitrinite (TPI(V) averages 0.5 to 0.6).

Morley coal seams contain proportions of the major maceral groups and of individual macerals similar to those in seams from Members 3 and 4 in the Paparoa Coal Measures (Fig 4.35 (b)) with the exception of the relative proportions of structured and unstructured vitrinite macerals (Table 4.13). Ohai coals contain far more structured vitrinite (TPI(V) averages 1.1) than coals of Members 3 and 4 (TPI(V) of 0.5 - 0.6). This difference in TPI(V) parallels differences in the macroscopic texture of the coals; Morley coals contain approximately 25% bright bands, which consist of structured vitrinite, whereas coals of Members 3 and 4 contain few bright bands. The lack of structured vitrinite in the Cretaceous Pike River Coals may be related to a flora more susceptible to degradation than the flora at Ohai, different mire chemistry in the two coalfields, or may indicate that Pike River mires were better drained. However, better drainage of all Pike River mires seems unlikely because the detrital layers in Member 3 and northern Member 4 mires indicates frequent flooding. In addition the frequent occurrence of "chuckies" in the coal indicate the presence of standing water above the peat. "Chuckies" are rounded pebbles and cobbles which are inferred to have fallen from between the roots of trees floating above peat. Morley coals are more like the southern Member 4 seams in which there is little evidence of detrital layers. The differences in the flora or mire chemistry of Morley and Pike River coals may reflect the fact that these mires, although both Haumurian in age, developed at different times in this period which spans 10 million years.

4.4.3.4 Comparison of the Petrography of Blocks from a coal seam in the Cretaceous Morley Coal Measures, Ohai Coalfield and a seam tn the Eocene Brunner Coal Measures, Pike River Coalfield

The Brunner Coal Measures at Pike River Coalfield consist of a single thick coal seam (3.5 to 13.5 m) over- and underlain by thin siltstone, sandstone and conglomerate. In the drillhole intersection described here (from drillhole 7), the seam is 12.2 m thick and is split by a parting 0.2 m from the base. The seam is low ash (4 %) and, macroscopically, appears bright with very occasional bright bands 1 mm to 5 mm in width. The chemistry and general petrography of particle pellet samples from the seam are described in Quick and Moore (1991). Petrographical data from the block samples, which were analysed by T. Moore, is listed in Shearer and Moore (in prep.).

General Comparison of Morley and Brunner Data

A comparison of maceral analyses for blocks from the Brunner seam and a Morley seam from the O/C4 horizon, Wairaki No. 6 mine is shown in Table 4.14 and Figure 4.36. The major difference between the microscopic analyses of the two seams are, firstly, the Morley seam contains more inertinite (8% as compared to 2%) and also more liptinite in some ply samples. Secondly, in terms of individual maceral proportions, the Morley seam contains more telinite and less corpocollinite and desmocollinite. In addition, when the analytical results for the Morley seam are recalculated to include the bright bands estimated in mine faces, it is apparent that the Brunner and Morley seams have very different TPI(V) values (0.5 and 1.0 respectively).

The contrast between the Morley and Brunner seams is even more apparent when the proportions of the major botanical components in the coals are compared (Fig. 4.37). The greatest difference between the two coals is the presence of 24% macroscopic plant organs/tissues (seen as bright bands) in the Morley seam. These bright bands are seen to consist of xylem tissue when examined microscopically (Fig. 4.23).

The proportions of microscopic plant organs/tissues and matrix components present in the Morley and Brunner seams are compared in Figure 4.38 and listed in Table 4.15. Major differences are

a) The common occurrence of oxidised plant organs/tissues in the Morley seam but their absence in the Brunner seam.
b) The presence of xylem tissue in the Morley seam and its scarcity in the Brunner seam.
c) The proportions of cell fillings in the matrix, 2% in the Morley seam, 18% in the Brunner seam.
d) The presence of generally greater and also more variable quantities of amorphous matrix in the Brunner seam than in the Morley seam.
e) The presence of bituminite in the matrix of only the Brunner seam.
f) The relative proportions of plant organs/tissues and matrix, the ratio of plant organs/tissues to matrix being equal to 0.6 in the Morley seam and 0.3 in the Brunner seam.

The constituent tissues of the plant components in the Morley and Brunner seams are shown in Figures 4.24 (Morley) and 4.38 (Brunner) and the important differences between the plant components common to both coals are as follows. Firstly, the proportions of suberinised cell walls and cork cell fillings in cork tissue are dissimilar; cork in the Morley seam has 81% suberin and 18% cork cell fillings whereas that of the Brunner seam has only 20% suberin but 80% cork cell fillings. Secondly, the proportions of suberinised cell walls and cork cell fillings in stem/roots with secondary growth differ; stem/roots in the Morley seam comprise 25% suberin and 11% cork cell fillings but Brunner stem/roots contain only 12% suberinite but 39% cork cell fillings. In addition, the proportion of cell fillings in unidentified poorly preserved tissue is only 7% in the Morley seam but is 18% in the Brunner seam.

Not only the types of botanical components but also the sizes of these components can be compared between the Morley and Brunner seams (Figs. 4.28 to 4.31, Morley and Figs. 4.40, 4.41, Brunner). The most important difference between the size distributions of the coals is that the Morley seam contains 3 size populations (Fig. 4.28) whereas the Brunner seam contains only 2 size populations (Fig. 4.40). The two smaller size populations in the Morley seam are comparable to the two populations in the Brunner seam; 'microscopic plant organs/tissues' in the Morley seam and 'plant organs/tissues' in the Brunner seam both range from about -1 to 8 Ø 2 to 0.004 mm), with means of 3.5 Ø (0.09 mm) and 4.6 Ø (0.04 mm) respectively. Matrix components range from 2 to 11 Ø (0.25 to 0.0004 mm) with a mean of 8.8 Ø (0.002 mm) in the Morley seam and from 3 to 11 Ø (0.1 to 0.0004 mm) with a mean of 8.3 Ø (0.003 mm) in the Brunner seam. However, the largest size population in the Morley seam, ranging from -6 to 2 Ø (64 to 0.25 mm) with a mean of -1.7 Ø (3.2 mm) and mostly composed of xylem tissue, has no equivalent in the Brunner seam.

The size distributions of individual microscopic components are shown in Figures 4.29 to 4.31 (Morley) and Figures 4.40 to 4.41 (Brunner). The size distributions of the plant organs, tissues and matrix components have similar ranges and means with the exception that the mean sizes of plant organs and tissues in the Brunner seam are consistently smaller than the mean sizes of the same types of plant organs and tissues in the Morley seam.

Comparative Usefulness of Maceral Data and Botanical Data

For comparison of the Morley and Brunner seams, botanical analysis provides more information on the differences between the seams than does maceral analysis. The maceral analyses merely show that the Morley coal a) is less degraded and b) contains less oxidised material than does the Brunner coal. In contrast, the botanical analyses showed the same differences as the maceral analyses (a) and b) above) and also that the Morley seam, as compared to the Brunner seam c) contains more oxidised plant organs/tissues but similar amounts of oxidised material, d) contains very significant amounts of xylem tissue, seen as bright bands in mine faces and e) contains distinctively different cork tissue.

Possible Reasons For the Differences Between the Coal Seams

The differences between the Morley and Brunner coal seams may reflect the presence of different mire floras, different drainage conditions or different chemistry. There is palynological evidence (Warnes, in prep.; Shearer, in prep.) that the flora in the Morley and Brunner mires was markedly different. The pollen found in Morley coal is dominated by gymnosperms, in particular, *P. mawsonii*, whereas the Brunner pollen is predominantly angiosperm. Different mire floras could explain the different types of cork tissue found in the two coals and also the consistently smaller plant organs in the Brunner seam; Eocene plants may have been generally smaller than those in the Cretaceous. The contrasting floras may also at least partially explain the presence of xylem tissue in Morley coal which forms the bright bands, the largest of the three size populations and also results in a high TPI(V) in Morley as compared to Brunner coal. Gymnosperm wood is more resistant to degradation than is angiosperm wood therefore woody tissue in the Morley mire would be expected to be better preserved. However, it seems unlikely that all the xylem tissue in Brunner coal was degraded but that whole stem/roots remained in the peat. It is more likely that Brunner mire flora simply produced less woody tissue than Morley flora.

Evidence that there was more severe degradation of Brunner than Morley peat is the higher proportion of amorphous matrix in the Brunner coal and the presence of bituminite, which is not present in Morley coal. Climate may also account for the difference in degree of tissue preservation in the two coals as well as the different mire floras. It is possible that the Eocene was warmer than the Cretaceous (Newman, 1989). Warmth encourages microbial activity, therefore increases rates of tissue decay and lowers TPI(V).

The lack of oxidised material in the Brunner coal is characteristic of New Zealand Eocene coals irrespective of depositional setting and may also reflect climatic conditions. Newman (1989) attributes the lack of inertinite in Brunner coal to constant flushing of raised mires by rainwater. In contrast Morley mires were, at times, better drained or in an area of lower rainfall, hence were drier.

4.5. SUMMARY

Conclusions about the petrography of the Morley and Beaumont coals can be divided into four sections, the maceral parameters used to interpret paleo-mire environments, the temporal variation in the coals, the character of the macerals in Morley coals as compared to coeval coal seams from Kaitangata, Greymouth Coalfield and Pike River Coalfield, and conclusions on the usefulness and interpretations possible from botanical analysis of coal.

For maceral parameters to be useful paleoenvironmental indicators, the origins of the macerals must be understood. Maceral parameters used for interpretation of Ohai Coalfield mire paleoenvironments are:

1) Proportion of liptinite: in Morley coals greater amount of liptinite in some coals may reflect concentration of liptinite during degradation, although a few liptinite and mineral matter rich layers were probably of detrital origin. In Beaumont coals, liptodetrinite is associated with mineral matter and was probably introduced to mires during flooding.
2) Proportion of inertinite: in Morley coals the quantity of inertinite in coal indicates the periodic relative dryness of the paleo-mires. The water table levels controlled rates of microbial oxidation of tissue, the amount of burning of surface vegetation, and the prevalence of aerobic oxidation.
3) TPI: the best preservation of vitrinite is seen in high ash coals (high TPI(V)), in which inertinite is most poorly preserved (low TPI(I)). The amount of tissue degradation of Morley peat reflected in TPI(V) of Morley coals is thought to have resulted from interrelated increases in nutrient supply, decreased acidity and raised water table associated with flood events and also during gradual flooding leading to mire death. In Beaumont coals the high TPI(V) values, compared to Morley coals, probably indicate that Beaumont mires were continually flooded. Low ash Beaumont coals may have developed adjacent to lake margins; the lack of degradation in this peat resulted from its remaining in an area of high water table after mire death.

The temporal variation in Morley and Beaumont coals can be evaluated at three scales:

1) Late Cretaceous to Eocene: The Cretaceous mires were less susceptible to flooding and may have been raised above the surrounding sediment as compared to the low-lying, flood-prone Eocene mires. The flora of the mires changed from a Cretaceous flora rich in gymnosperms with subordinate angiosperms and pteridophytes to vegetation with both angiosperms and gymnosperms in the Eocene.
2) Mire development throughout Morley Coal Measures accumulation: Mire horizons do not appear to have distinctive petrographic characteristics except for seams in the lowest sedimentary horizons studied in both sub-basins (O/C2 and M/C1). Mires in these horizons probably had relatively low water tables resulting in increased tissue degradation in both basins and increased oxidation of tissue in the Mossbank mires.
3) Development of individual Morley mires: plant growth and peat accumulation may have been initially rapid but declined during mire development, because the nutrient supply diminished and acidity increased. As the mires developed drier conditions became more common, burning of surface vegetation and microbial oxidation of coal were more prevalent and peat was subject to intense aerobic decay for longer periods because the water table was lower. Mire death was gradual in most cases and the slowly rising water table limited the amount of degradation of peat in the uppermost part of mires. Flood events affected mires, particularly the longer lived mires, interrupting their development and resulting in environmental conditions similar to those in which mire growth originated. Flora in mires was dominated by gymnosperms and differed substantially from non-peat forming vegetation in which angiosperms were preeminent. Mire forming vegetation developed from communities containing species common to both mire forming and non-mire forming vegetation. However, as peat accumulated, the species susceptible to high acidity and intolerant of low nutrient supplies decreased in number, and in many mires the flora became dominated by *Phyllocladidites mawsonii.*

The general maceral character of Morley coals is similar compared to that of coals developed coevally in the Kaitangata, Greymouth and Pike River Coalfields. However, the following exceptions exist:

1) Taratu Formation, Kaitangata Coalfield: Inertinite rich coals in the Benhar and Mt Wallace Members, particularly inertodetrinite rich layers, are unlike any Morley coal. Burning of mire vegetation/peat and transport of oxidised material was more common in the Benhar and Mt Wallace Members than in the Morley Coal Measures.
2) Rewanui Member, Paparoa Coal Measures, Greymouth Coalfield: The maceral textures in Rewanui coal indicate that Rewanui mires developed in a wider range of geographic settings and with more varied flora than Morley mires.
3) Members 3 and 4, Paparoa Coal Measures, Pike River Coalfield: Morley coals are similar to the southern coals of Member 4 but differ from the northern coals of Member 4 and coals of Member 3, which contain numerous detrital layers and are interpreted as having

been frequently flooded. All Pike River coals are more degraded than Morley seams and this contrast may reflect different floras or different mire chemistries in the two coalfields.

Petrographic analysis of the types and sizes of the botanical components in coal may be more useful for distinction of differences between coal seams than are standard maceral analyses. The contrasting botanical characteristics of a Cretaceous Morley seam and an Eocene Brunner seam may be the result of different floras, drainage conditions or mire chemistry. The major differences between the seams are:

1) The presence of secondary xylem tissue forming bright bands in mine faces but the absence of both bright bands and secondary xylem tissue in Brunner coal. Palynological data indicate that this difference may have resulted from the different floras in the Morley and Brunner mires; the Morley flora was dominated by gymnosperms whereas angiosperms were preeminent in Brunner mires.
2) The secondary xylem in Morley coals creates a coarse size population in a trimodal distribution whereas the absence of macro-banding in the Brunner coal is the result of an absence of secondary xylem tissue leading to coal with a bimodal size distribution.
3) Different types of cork tissue in the two coals, probably also the result of different floras.
4) Greater amounts of amorphous matrix in Brunner coal as compared to Morley suggesting that degradation was more complete in the Brunner mire, possibly because temperatures were higher.
5) A lack of oxidised material in Brunner coal in comparison to Morley coal, probably because Brunner mires were more constantly wet.

CHAPTER 5

PALEOENVIRONMENTAL MODELS FOR CLASTIC SEDIMENTS AND MIRES OF THE MORLEY AND BEAUMONT COAL MEASURES

In this chapter, conclusions on the sedimentary characteristics of the Morley and Beaumont Coal Measures (from Chapter 2), and on the chemistry and petrography of their coals (Chapters 3 and 4) are integrated into models of the depositional environments in which clastic sediments and peat accumulated. In addition, the nature of Morley and Beaumont sediments and coal are contrasted and reasons for the variations between coal measures suggested. Finally the development of coal measure sediments at Ohai and other Cretaceous-Tertiary coalfields is compared.

As stated in Chapter 2, the sedimentary planform of fluvial systems cannot be determined from the lithological data available at Ohai. However some features of channel behaviour, such as channel mobility, can be interpreted. In addition, the probable response of fluvial systems to the tectonic setting of the coalfield can be evaluated for the Morley Coal Measures. Because channel planform cannot be resolved, the channels depicted on block diagram models are not intended to be representative of paleo-channel forms nor to indicate the locations of channels within sub-basins. Rather, they are intended to indicate only the presence of drainage systems and their proximity and distribution relative to mires and floodplain sediments.

5.1 MORLEY COAL MEASURES

5.1.1 Sedimentary Environments

Sedimentological analysis of drill core data, outcrop in opencast mines and composite cross-sections show that deposition of the Morley Coal Measures occurred in two dissimilar and non-contemporaneous sedimentary environments:

1) An environment characterised by fluvial channels transporting sandy sediment in a floodplain with little mire development ('S'-environment).
2) An environment in which mud-bearing streams generally flowed between extensive mires and in which little coarse sediment was deposited ('C'-environment).

It is likely that the occurrence of the 'S'- and 'C'-environments was controlled by tectonic activity, which increased relief in the sediment source area, thereby increasing sediment production and facilitating transport of sediment down slope to the coalfield. In addition, the Mossbank Basin was probably often sheltered from input of coarse sediment by the presence of two basement highs (the Bluebottle and Moretown Highs). The relative relief on these highs was created by local tectonic activity. The Ohai Basin may also have been periodically sheltered from sediment input by local basement highs although no evidence of such structures has been preserved. Another possibility is that aggradation of sediment in the Ohai Basin resulted in switching of fluvial deposition to a locus outside the coalfield.

It is likely that the dominant direction of drainage in both the 'S'- and 'C'-environments was towards the southern margin of the coalfield (Twinlaw and Wairio Faults). If through-drainage occurred, it did not have any significant effect on the Morley sediment for which data is available. From this fact, and the characteristics of the 'S'- and 'C'- environments described in the following paragraphs, it is possible to construct general models for accumulation of Morley sediment. The five models (Figs. 5.1 and 5.2) depict deposition in an 'S'-environment in both the Ohai (Fig. 5.1 (a)) and Mossbank (Fig. 5.1 (b), (c)) Basins, deposition in the early stages of 'C'-environment development (Fig. 5.2 (a)) and following mire establishment (Fig. 5.2 (b)).

'S'-environments differed between the Ohai (Fig. 5.1 (a)) and Mossbank (Fig. 5.1 (b), (c)) Basins. In the Ohai Basin, channel character varied, probably in response to tectonic activity in the coalfield. Unstable channels, depositing sandstone 'sheets', occurred in areas of slower subsidence, nearer the basin perimeter. Stable channels, depositing sandstone 'ribbons', were more common in areas of rapid subsidence (towards the centre and the south of the Ohai Basin). It is likely that only one stable channel existed at any time. The Bluebottle High was an important structural control on Ohai Basin drainage and may also have sometimes acted as a sediment source. Both stable and unstable channels occurred within floodplains which were often vegetated but in which mire development was rare.

In the Mossbank Basin 'S'-environments, periodic short-lived fluvial events spread coarse clastic sediment across the sub-basin in 'thin' sandstone sheets (Fig. 5.1 (b)) sourced from the west or north. Between fluvial events carbonaceous mudstone was deposited (Fig. 5.1 (c)) in shallow lakes and/or from low energy mud-bearing streams associated with small mires. This alternation of fluvial and lacustrine deposition may reflect episodic tectonic activity which allowed coarse-grained sediment to be transported into the Mossbank Basin.

Mire development was uncommon in most 'S'-environments, except for the youngest 'S'-environment in the Ohai Basin (O/S4). There is no clear evidence as to why the paleoenvironment during deposition of the O/S4 horizon was more conducive to mire development than were other 'S'-environments. In the Mossbank Basin 'S'-horizons, coal seams occur only associated with extensive mudstone or carbonaceous mudstone units, therefore mires probably developed during periods of little sediment input into 'S'-environments. In the Ohai Basin 'S'-environments mires may also have developed during periods of low energy sediment deposition. Alternatively the mires may have occurred in local areas of the sub-basin, to which sediment influx was restricted because of the stability or remoteness of fluvial channels. Another possibility is that mires were associated with fluvial deposition but were raised above local sedimentation either by a domed geometry or development on abandoned channel sandstone.

'C'-environments in both sub-basins were dominated by mires (Fig. 5.2 (b)), except during initial mire development when carbonaceous mudstone was deposited in lakes and/or streams while mire flora became established (Fig. 5.2 (a)). Mires were particularly widespread and long-lived in the most southern parts of the Ohai and Mossbank Basins for which data is available. Only localised deposition of sand occurred in 'C'-environments, because channels mainly transported only fine-grained sediment. Flooding of channels into mires was rare, as evidenced by the lack of partings in seams and low mineral matter content of coal. The lack of coarse-grained sediment in channels probably indicates low hydrodynamic fluvial activity, therefore channels were unlikely to migrate and inundate swamps. In addition, mire vegetation probably stabilised channel margins, preventing migration, and acted as a baffle to floodwaters. Mires may also have been domed and thus raised above local flood sedimentation. Associated with the relatively high proportion of organic material in 'C'-environments, both sediments and mineral matter in coal were intensely leached.

5.1.2 Morley Mires

The similarity of the chemical, petrographical and palynological character of all Morley coal seams between and within sedimentary horizons, suggests that general mire character was not highly variable at different times or in different parts of Ohai Coalfield. However, it is possible that differences in the mineral matter in peat may have been overprinted during leaching. In addition, the vitrinite rich character of the coal means that significant variability in coal is unlikely to be identified by standard maceral analyses.

There are only two instances of quantifiable petrographic differences between coal seams. First, coal seams in the Mossbank Basin generally contain more partings, mineral matter and better preserved tissue (higher TPI(V) values) than do Ohai Basin seams. These differences suggest that flooding of Mossbank mires was more common than was flooding of Ohai mires Therefore Mossbank peat either developed in conditions of relatively high water table hence was less degraded and/or nutrients derived from the mineral matter encouraged woody (decay-resistant) plant growth. The second difference is the low TPI(V) values and high liptinite content of coal from the lowest 'C'-horizons studied in the Ohai and Mossbank Basins (O/C2 and M/C1), as compared to seams in all other horizons. The peat in these mires was more completely degraded, possibly in an environment with a low water table. The high proportion of inertinite in M/C1 coal is supporting evidence that M/C1 mires were relatively dry.

Greatest variation in Morley coal character occurs within rather than between seams. From the following observations on the sedimentary relationships, chemistry, petrography and palynology of coal seams, a general model for the development of Morley mires has been constructed (Fig. 5.3).

1) All coal is vitrinite rich.
2) The inertinite content of coal is generally greater towards the centre of coal seams and away from partings. The same trend is seen in the presence of the highest percentages of inertinite in coal with the lowest ash content and also the occurrence of the inertinite-rich maceral assemblages 3 and 4 in the centre of seams.
3) The character of inertinite in coal indicates that oxidation of plant tissue occurred during periods of relatively low water table. Inertinite precursors were formed during burning of surface vegetation, drying of exposed plant material and microbial degradation of plant tissue.
4) TPI(V) is generally lower towards the seam centre and away from partings. The same relationship is seen in the increase of TPI(V) in high ash samples.
5) TPI(V) variation can generally be attributed to flooding of peat as well as to the nutrient rich substrate on which mires developed. The factors affecting plant growth rates, peat accumulation rates and degradation rates are all interdependent. Flooding of peat increased nutrient supplies, decreased acidity and raised water tables. Nutrient supplies and acidity affect plant growth rates and stature, therefore influence rates of peat accumulation. The level of the water table, together with acidity and the nature of plant tissue and the rate at which plant material accumulates, all affect the degree to which plant material is degraded.
6) The proportion of 'bright bands' in coal decreases towards seam centres and away from partings.
7) Nearly all 'bright bands' in coal are formed dominantly (96%) of wood, that is, secondary xylem tissue, together with a small quantity of cork tissue (4%).
8) The plant organ/tissue to matrix ratio may vary within seams in a similar way to the proportion of bright bands. However to confirm this trend more data is required.
9) Coal generally contains little mineral matter and seams contain few partings.
10) Coal seams in both outcrop and drill core usually grade vertically into rooted carbonaceous mudstone and the mineral matter content of coal increases towards seam roofs, floors and partings.
11) In composite cross-sections, coal seams are usually vertically and laterally adjacent to carbonaceous mudstone.
12) Palynological counts in Morley coal are dominated by gymnosperm pollen, in particular *Phyllocladidites mawsonii* (which can compose up to 90% of the total count).

13) The proportions of angiosperm pollen increase and proportions of *P. mawsonii* generally decrease at coal seam bases and tops as well as into sediments. Counts of spores are similar in both sediments and in coal although fewer spores are found in plies in seam centres.
14) Pollen associations in the coal indicate that flora present during initial mire development may have consisted of species from both peat forming (gymnosperm dominated) and non-peat forming (angiosperm dominated) plant communities. As mires developed the species less tolerant of acidity and requiring better nutrient supplies decreased in number, resulting in a flora dominated by gymnosperms.

In the proposed model (Fig. 5.3) there are two end member types of peat which graded into one another relatively rapidly. The end members are:
1) Peat containing well-preserved plant tissue and high proportions of woody plant organs (probably roots) but relatively little oxidised plant material and variable percentages of mineral matter. The nearer this peat was to the the base or top of the mire, or to partings, the more mineral matter it generally contained.
2) Peat containing less well-preserved plant tissue, fewer woody plant organs than type 1, variable proportions of oxidised plant material but often more than in peat type 1, and little mineral matter.

Peat type 1 developed at the base of mires and also following flood events. Incorporation of mineral matter into peat occurred from the nutrient rich substrate which probably also promoted rapid and woody plant growth. Inundation of mires, creating high water tables and introducing mineral matter, was more common in this early phase of mire development during which mire flora became established. Rapid peat accumulation together with generally high water tables in mires resulted in relatively little degradation of plant material. Wood was preserved because lignin is not degraded in the anaerobic environment which peat layers quickly reached.

Peat type 1 also developed preceding flood events and in the period before mire death when gradual flooding of peat increased nutrient supplies, decreased acidity and raised water tables, decreasing tissue degradation and oxidation of plant tissue. Alternatively, in some mires rapid burial of the peat by flood deposited sediment may have submerged peat layers below the aerobic zone of decay, thereby reducing the degree to which plant material in these layers was decayed or oxidised.

Peat type 2 developed once mires were established and where no flooding was occurring. Poor nutrient supplies in the established mire coupled with low pH conditions stunted and slowed plant growth. Less wood was produced and degradation of plant tissue was more complete because low water tables and slow peat accumulation left peat layers in the aerobic zone of decay for long periods. In addition, oxidation of plant tissue occurred during dry periods because burning of vegetation and drying of plant material at the surface and microbial oxidation were more likely.

The flora which contributed to both peat types was dominated by gymnosperms. Although the mire flora appears to have changed from initial mire development to established mire communities (*P. mawsonii* became more prevalent in the vegetation while other gymnosperms and angiosperms declined in number) there is no palynological evidence that the character of mire floras is directly related to peat type. However, the flora forming mires in which clean peat accumulated differed markedly from the general flora of the coalfield. In the non-peat-forming communities angiosperms were the dominant component of the flora and gymnosperms and pteridophytes minor components in contrast to the gymnosperm-rich mire flora.

Although the vertical changes in peat type can be modelled from the Morley coal analyses, insufficient sample data exists to quantify relative tissue preservation and oxidation between mire margins and centres. However, if the same controls on tissue degradation were operative throughout the mires, it seems reasonable to assume that peat at mire edges was well preserved and woody because it accumulated adjacent to streams, that is, in an area of raised water table and high nutrient supply. In addition, the flora at mire margins was probably similar to the initial mire vegetation, consisting of species common to both peat-forming and non-peat-forming communities.

5.2 BEAUMONT COAL MEASURES

5.2.1 Sedimentary Environments

Analysis of Beaumont sediments revealed that deposition of the Beaumont Coal Measures occurred in 3 different environments:

1) 'S'-environments in which fluvial channels transporting and depositing both coarse- and fine-grained sediment were predominant.
2) 'C'-environments which were low energy environments where channels transported and deposited mainly fine-grained sediment in widespread shallow lakes. In the Mossbank Basin 'C'-environments were, at times, contemporaneous with 'S'-environments.
3) A 'C'/S' environment in the Ohai Basin in which channels transporting both mud and sand drained into shallow lakes.

The occurrence of the above environments probably was significantly influenced by both tectonic and autocyclic sedimentary controls. Production and transport of sediment to sub-basins was controlled by tectonic activity, as was the presence of the Bluebottle High.

The effect of the Bluebottle High on the Beaumont sequence is far less marked than on the Morley sequence, suggesting that tectonic controls on sedimentation declined from the Cretaceous to the Eocene. In addition, the separation in time of the 'S'- and 'C'-environments, attributed to tectonic activity for the Cretaceous sediments, is not as clear-cut in the Eocene. This is seen in the interfingering of horizons M/C2, M/S1 and M/S2 as well as the presence of the O/C-S horizon. The separation in space, rather than in time, of the M/C2, M/S1 and M/S2 environments could have been related either to local patterns of tectonic subsidence or to the character of fluvial deposition.

From the characteristics of the Beaumont depositional environments, described in the following paragraphs, 3 depositional models (Fig. 5.4) have been constructed for deposition of Beaumont sediments. The models picture deposition in an 'S'-environment (Fig. 5.4 (a)), a 'C'-environment (Fig. 5.4 (b)) and in the 'C-S'-environment (Fig. 5.4 (c)).

In the 'S'-environments (Fig. 5.4 (a)), either widespread multiple channels and/or migrating channels deposited sand over large areas. The channels were laterally adjacent to floodplain areas in which finer-grained sediment was deposited and probably frequently eroded by subsequent channel activity (particularly in the Mossbank Basin). The only evidence of mire development in an 'S'-environment is a single coal seam in horizon O/S.

'C'-environments were dominated by shallow lakes into which channels bearing mainly fine-grained sediment drained. Short-lived episodes of coarse-grained fluvial deposition occurred but this deposition did not extend basin-wide. Mires probably developed on lake margins and where sediment infilled lakes. Local tectonic subsidence may have favoured peat preservation by rapidly moving peat below the local level of sedimentation, therefore peat was not eroded by later channel activity.

The 'C-S'-environment which developed in the Ohai Basin was probably similar to 'C'-environments except for the presence of persistent, rather than occasional, sand-bearing channels. As a result, more sandstone was deposited in the 'C-S'-environment than in 'C'-environments. In addition the lack of carbonaceous mudstone in the 'C-S'-horizon as compared to the 'C'-horizons, suggests that organic sedimentation was not as common in the 'C-S'-environment as in 'C'-environments. The few mires which developed in the 'C-S'-environment may have occurred on lake margins.

5.2.2 Beaumont Mires

Compared to Morley mires, Beaumont mires were relatively small and short-lived. Because mires were rarely protected from flooding and often developed on lake margins, water tables in the mires were permanently high. The few Beaumont coal seams which are low in mineral matter may be the result of mires which developed remote from channels. In addition, if these mires were in an area of poor drainage, increased acidity of the mire environment would have resulted in clay flocculating at mire margins during flooding and never reaching mire centres. The frequent flooding of most Beaumont mires resulted in high water tables and introduced both liptinite precursors and mineral matter to the peat. The mineral matter supply was a constant nutrient source to mire flora promoting woody, decay-resistant plant growth. High water tables reduced both the amount of oxidation and the degree of degradation of plant tissue, resulting in well-preserved peat which contained few inertinite precursors. The floral character of the Beaumont mires is unlikely to have been a factor in the good preservation of plant material because pollen data suggests that mire flora was composed of both angiosperms, which are susceptible to degradation, as well as gymnosperms. However mire flora probably contained more gymnosperms than did other Ohai plant communities in the Eocene.

5.3 CONTRASTING CHARACTERISTICS OF THE MORLEY AND BEAUMONT COAL MEASURES

The major contrasts between the Morley and Beaumont Coal Measures are as follows:

1) In the Morley Coal Measures coarse-grained sediment was effectively excluded from entering the Mossbank Basin for long time intervals and also, periodically, from the Ohai Basin. In the Beaumont Coal Measures, although coarse-grained sediment was excluded from both of the sub-basins for substantial time intervals, there is more evidence of contemporaneity of 'S'- and 'C'-environments.
2) Coal seams occur in all Morley sedimentary horizons whereas coal seams occur only in the 'C'- and 'C-S'-environments of the Beaumont Coal Measures (with the exception of a single coal seam in the O/S horizon).
3) Morley coal seams are generally more extensive and thicker than Beaumont seams.
4) Morley coal generally contains less mineral matter than Beaumont coal.
5) Morley coal has lower volatile matter values and H/C ratios than Beaumont coal.
6) Morley coal generally has a lower lipinite content and higher inertinite content than Beaumont coal.
7) Morley coal contains less suberinite and liptodetrinite than Beaumont coal and Beaumont coals contains resinite which fluoresces green in white light. This type of resinite is not present in Morley coal.
8) Morley coal has much lower TPI(V) values than Beaumont coals.
9) Palynological counts in Morley coal are dominated by gymnosperm pollen. In contrast, in the Beaumont coal both angiosperm and gymnosperm pollen are important and pteridophyte spores occur in very small proportions. Furthermore, the pollen form *Phyllocladidites mawsonii*, which occurs in significant proportions in Morley coal, is uncommon in Beaumont samples.

The non-contemporaneity in both Morley and Beaumont sequences of alternating sedimentary environments dominated by coarse- or fine-grained sedimentation has been attributed here largely to the effectiveness with which the sub-basins in the coalfield were isolated from input of coarse-grained sediment, probably by the presence of basement highs. In addition, climate and/or floral character or relative relief in the sediment source area may have affected the amount and type of sediment transported to the Ohai Basin. The presence of basement highs and relative relief in the region were controlled by the frequency and character of tectonic activity. The increased contemporaneity of widespread coarse- and fine-grained sedimentation in the Beaumont Coal Measures (difference 1) may therefore reflect a decline in tectonic activity in the Eocene, as compared to the Cretaceous. The greater continuity of Eocene than Cretaceous sediment over the Bluebottle High also suggests a decline in tectonically induced relief as does the Eocene absence of the Moretown High which significantly affected Cretaceous sedimentary deposition.

All of differences 2) to 8) can be explained by the different sedimentary environments in which mires developed together with variation in mire floras and possibly in the geometry of mires. The presence of coal seams in Morley 'S'-environments (difference 2) is likely to have resulted from stable channel development or less continuous sand supply in the Cretaceous 'S'-environments. In contrast, in Beaumont 'S'-environments widespread deposition of sand occurred in and from unstable channels, flooding and eroding any mire vegetation.

Larger and longer lived mires in the Cretaceous as compared to the Eocene (difference 3) probably resulted from the greater suitability of Cretaceous sedimentary environments for mire formation and possibly also because Cretaceous flora was more suited to development of mires. The long life span of Morley mires may have reflected the lack of sediment in the 'C'-environments and channel stability in both 'S'- and 'C'-environments. In addition, Morley mires may have been domed, inhibiting flooding. In contrast, Eocene mires were probably not domed and did not stabilise channels as did Morley mires.

The greater quantities of mineral matter in Beaumont coal as compared to Morley coal (difference 4) resulted from the frequency of flooding of Beaumont mires. Flooding, as described above, was related to the widespread distribution of clastic sediments in Beaumont 'C'-environments and possibly also to the relatively flat geometry of Beaumont mires.

The contrasts in volatile matter values, H/C ratios and liptinite and inertinite content of Morley and Beaumont coals (differences 5, 6 and 7) are all related. Flooding of Beaumont coal introduced fine-grained liptinite precursors and prevented oxidation (production of inertinite precursors) by keeping the water tables high. In addition, Beaumont flora have produced more cork tissue (suberinite precursor) and resin as compared to Morley flora. In contrast, there was little opportunity for introduction of liptinite precursors to Morley mires during flooding and periodic dry periods resulted in oxidation of plant tissue. The high liptinite, low inertinite nature of Beaumont coal leads to its high volatile matter values and also high H/C ratio (liptinite is volatile and hydrogen rich whereas inertinite is relatively volatile and hydrogen poor).

The difference in TPI(V) values for Morley and Beaumont coal (difference 8) are largely related to the frequency of flooding of mires. High water tables reduce the degree to which peat layers are degraded because the layers are rapidly buried to the anaerobic zone of decay where degradation rates are slow. Therefore Beaumont plant material was little degraded because water tables were constantly high in Beaumont mires. In contrast, in Morley mires water tables fluctuated, particularly once mires were established, leaving peat layers longer in the zone of rapid aerobic decay. In addition, the constant nutrient supply in Beaumont mires may have promoted woody plant growth.

The differences in mire flora between the Cretaceous and Eocene at Ohai reflect the general world-wide change in flora as angiosperms diversified and became more important in plant communities. Moreover Newman (1989) postulates a relatively warmer climate in New Zealand during the Eocene than the Cretaceous. Such a climatic variation would have a major effect on the plant species which will thrive in particular drainage conditions in any area.

5.4 REGIONAL SETTING OF THE MORLEY AND BEAUMONT COAL MEASURES

Conclusions reached for the Morley and Beaumont Coal Measures can be compared to data available for other Cretaceous-Tertiary South Island coalfields. Such comparison enables the regional setting of the coalfield to be understood and adds to the knowledge of environments in New Zealand Cretaceous-Tertiary rift basins. In this section four coalfield sequences are briefly compared on the bases of age, general tectonic setting, the style of and controls on sedimentation, and coal petrographic character.

As mentioned in Chapter 1, Ohai Coalfield developed contemporaneously with the Kaitangata, Greymouth and Pike River Coalfields (locations and general stratigraphy shown in Figs. 4.32 and 4.34) during a period of Late Cretaceous extension in the New Zealand continental crust. This extension resulted in the formation of numerous fault-controlled rift basins in which coal measures accumulated. At Pike River Coalfield, as at Ohai, there is an unconformity separating Late Cretaceous and Eocene coal-bearing formations. Kaitangata coal measure sediments have been dated as Late Cretaceous to earliest Eocene, however the youngest coal seam is Paleocene in age. At Greymouth, sedimentation was continuous from the Late Cretaceous into the Paleocene but there was a break in deposition from the Late Paleocene into the Eocene.

All four coalfields mentioned above developed in terrestrial faulted sedimentary basins. At Ohai both the Morley (Cretaceous) and Beaumont (Eocene) Coal Measures developed in a west-east oriented half graben. Fault movement on the basin axis was in the same direction during the Cretaceous and Eocene, but during the Eocene there was reversal of the sense of movement on some faults within the coalfield. At Kaitangata, Cretaceous sedimentation also occurred in at least one half-graben (Raymond, 1985) with the major fault (Castle Hill Fault) oriented north to north-northeast. However, during the early Paleocene the direction of movement on the axial fault reversed (Browne, 1986) allowing coal measure sedimentation to become widespread rather than confined to a half-graben. Greymouth and Pike River Coalfields developed in a single faulted sedimentary basin with a major north-northeast trending fault zone on the east side (Newman, J., 1985a). Cretaceous to Eocene coal measure sediments in this basin display no evidence of reversed fault movement during the Tertiary.

Tectonic control of sedimentary deposition was prevalent during the Cretaceous in all four coalfields although their specific depositional environments differed. Cretaceous sediments at both Ohai and Kaitangata are characterised by alternating horizons of dominantly coarse- or fine-grained sediment. These horizons represent alternation of coarse-grained fluvial deposition with widespread mire formation. At Ohai these major changes in environment are attributed to episodic tectonic activity which increased the relative relief on basement highs within the coalfield and perhaps also in sediment source areas. There is also evidence that there was tectonic control of fluvial channel form as well as occurrence of channels; channel stability was affected by subsidence rates and channels may have been entrained along areas of maximum subsidence. Episodic tectonism may also have influenced variation in sedimentary environments at Kaitangata although Raymond (1985) was unsure whether the variation in environment at Kaitangata related to tectonic activity, switching of the major regional fluvial axis as the result of sedimentary controls, or to eustasy.

Development of Cretaceous fluvial and lacustrine environments at Greymouth coalfield is attributed to block faulting by Newman, J. (1985a). In the Paparoa Coal Measures at Greymouth there is alternation of widespread fluvial and lacustrine deposition although these environments were often contemporaneous, in contrast to the alternating fluvial and mire dominated intervals at Ohai and Kaitangata. In the Rewanui Member of the Paparoa Coal Measures, channel locations may have been controlled by subsidence, as at Ohai. At Pike River Coalfield the Paparoa Coal Measures exhibit alternation of coarse- and fine-grained sediment only in Member 4. The mechanism suggested for this alternation (Newman, J., 1985a) is switching of the fluvial axis to either side of a tectonically controlled basement high.

Changes in the tectonic environment from the Cretaceous to the Tertiary at Ohai, Kaitangata, Greymouth and Pike River were associated with changes in patterns of sediment deposition. At Ohai, the alternation of dominantly coarse- and fine-grained sedimentation became less marked and fine-grained sediments were deposited in lacustrine environments with fewer mires than in the Cretaceous. Tectonic activity is considered to have had a less significant effect on sedimentary style as basement highs ceased to control fluvial distribution. A similar decline in localised tectonic activity is inferred in the early Tertiary at Kaitangata (Browne, 1986) although alternation of fluvial- and mire-dominated environments continued until the end of the Paleocene. Widespread subsidence at Kaitangata rather than local basin development became the most important influence on the distribution and type of sedimentary accumulation. In addition, widespread subsidence resulted in marine incursions into Kaitangata Coalfield during the Tertiary.

At Greymouth and Pike River there is less clear evidence for tectonic control of Tertiary Brunner Coal Measure sedimentation as compared to the Cretaceous Paparoa Coal Measures, therefore the effect of tectonic activity may have declined into the Tertiary, as at Ohai and Kaitangata. Marine influence on Tertiary coal measures at Greymouth and Pike River parallels that at Kaitangata. However, in contrast to both Ohai and Kaitangata, during the Tertiary at Greymouth and Pike River there was a single, long-lived period of mire development, resulting in a thick coal seam. Ohai is the only coalfield of the four in which Tertiary mire development was relatively insignificant.

In a broad comparison of Morley and other Cretaceous coals, it appears that all these coals are superficially petrographically similar but possess specific differences which indicate differing mire environments in all the coalfields. The Benhar seams from Kaitangata often contain far more inertinite than do Morley coals and also exhibit a greater range of TPI(V) values. The inertinite-rich coals indicate substantial periods of low water table in the Kaitangata mires and also hydrologic redeposition of oxidised plant tissue which did not occur at Ohai. When compared to Cretaceous coal from the Rewanui Member of the Paparoa Coal Measures (Greymouth Coalfield), Morley coal has less variable maceral assemblages, indicating that Rewanui mires may have formed in a greater range of environments than Morley mires. Members 3 and 4 of the Paparoa Coal Measures at Pike River Coalfield have TPI(V) values much lower than those for Morley coal. The differences in the preservation of plant tissue in the Morley and Pike River coal may relate to different mire floras or chemistries in the two areas.

In summary, coal measure development in rift basins was relatively synchronous at Ohai, Kaitangata, Greymouth and Pike River Coalfields during the Cretaceous and Tertiary. In all of these coalfields, tectonic activity was a major control on Cretaceous sedimentary style but declined in importance into the Tertiary. In addition, most of the Cretaceous coals from the four coalfields are broadly similar, although they exhibit specific differences from which variations between mire environments can be inferred. Thick peats accumulated during the Cretaceous in all the coalfields; however during the Tertiary significant Paleocene mires formed at only Greymouth and Kaitangata and significant Eocene mires occurred at only Greymouth and Pike River. Comparison of these coalfields demonstrates the widespread effects of tectonism on the accumulation of clastic sediments and mire development during the Cretaceous and Tertiary. Tectonically induced separation of coarse-grained fluvial deposition and mires in time or space allowed accumulation of thick peats. Furthermore, the nature of tectonism and patterns of sedimentary accumulation can be compared through the Late Cretaceous to the Early Tertiary, a period in which there is considerable worldwide interest.

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